

**ENVIRONMENTAL CHANGE IN THE EASTERN TROPICAL PACIFIC OCEAN:
REVIEW OF ENSO AND DECADAL VARIABILITY**

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ABSTRACT

Interannual variability of the physical environment in the eastern tropical Pacific Ocean (ETP), and biological effects of this variability, are reviewed and compared to variability in the northeastern Pacific. El Niño/Southern Oscillation (ENSO)-scale variability of 2-7 year periods is dominant in the eastern equatorial Pacific and decadal-scale variability of 10-30 year periods is dominant in the northeastern Pacific. In the warm pool at the center of the ETP, temporal variability at any scale is relatively low. ENSO warm (El Niño) and cold (La Niña) events have had a variety of effects on marine populations and ecosystems, but these effects are generally followed by recovery within a few years. El Niño effects such as mortality or reproductive failure are most severe on populations dependent on local feeding or breeding grounds in coastal waters or on islands. Decadal variability has also caused change in populations and ecosystems. Most of these effects have been observed in the California Current, Gulf of Alaska, and other well-studied regions of the Pacific. The 1976-77 phase change or “regime shift” is the most well-known case of decadal variability. It affected the physical environment throughout the Pacific Ocean and had major effects on North Pacific ecosystems. No regime shift has been detected in the ETP since 1977. However, ENSO variability continues, an unusually persistent warming prevailed in the early 1990’s, and the thermocline has shoaled in the ETP warm pool area since 1980. Potential population effects on dolphin stocks are discussed. Interaction of environmental changes with other factors, such as fishery stress or mortality, may also induce population effects.

INTRODUCTION

Oceanographers have found that the ocean environment varies over every time scale that can be resolved as instrumental records have been extended, more accurate proxy records have been retrieved and calibrated, and these records have been analyzed with new statistical tools. The ocean environment in the eastern tropical Pacific Ocean (ETP) varies seasonally, interannually, and on longer time scales (decadal and climate change). Sorting out variability at these scales is necessary when attempting to detect environmental change and to interpret or predict its effects.

Seasonal variability exceeds interannual variability at the ocean surface, except within 5-10° of the equator in the Pacific (Fig. 1, also Delcroix 1993). Interannual variability is relatively strong in the eastern equatorial Pacific, due to the natural cycle of the ocean-atmosphere system called the El Niño/Southern Oscillation (ENSO). Variability in the equatorial Pacific, particularly in the central and western Pacific, is dominated by the El Niño/Southern Oscillation (ENSO) with periods of 2 to 7 years. Seasonal variability associated with the wind-driven equatorial cold tongue is strong in the eastern equatorial Pacific. This review will consider seasonal variability only to provide a perspective for patterns of interannual variability.

Instrumental records of environmental variables with sufficient temporal coverage to resolve interannual and longer-term variability either at a point or in a region of the ocean do not begin until about 1950 in the eastern Pacific, except for a few shore stations

on the U.S. coast¹. Coral records of isotope ratios have the potential to extend records of interannual and annual variability back beyond instrumental records, but interpretation of temperature, salinity, biological, and methodological effects is not always unambiguous. The longest published records for ETP cores extend to about 1600 (Gagan et al. 2000). Interannual and decadal variability in eastern equatorial Pacific (NINO3 region) SST are illustrated in Fig. 2 (Mann et al. 2000). The NINO3 record has been reconstructed back to 1650 using proxy data from tree rings, corals, sediments, and ice cores. Changes that have occurred over the last few decades are grossly similar to changes that have occurred for centuries, although modulations of the details will be discussed below.

Climate variability in the ocean, meaning variability on interannual and longer time scales, has been treated in two ways (Schwartzlose et al. 1999). For the purpose of this review, these two approaches to analyzing climate variability will be labeled as “spectral” and “regime”. The spectral approach uses statistical methods of time series and spectral analysis to decompose variability into trends, periodic oscillations, and random fluctuations. Moron et al. (1998) list 32 studies of global SST variability published between 1990 and 1996, all utilizing various statistical techniques to extract multiple time scale signals (the spectral approach). Long-term trends in such analyses, with the possible exception of global warming forced by greenhouse gasses, most likely represent low-frequency oscillations that are not resolved by short time series (Ware and Thomson 2000). The regime approach uses different statistical methods to break up time series into “regimes” characterized by relatively stable means and patterns of physical and biological variables, separated by rapid climate or regime shifts of synchronous change in these variables (Ebbesmeyer et al. 1991, Beamish et al. 1999). There are statistical methods, involving empirical orthogonal function or principal component analysis, that make no assumption about the spectral or regime-like nature of temporal patterns (cf. Zhang et al. 1997). The spectral and regime approaches to analyzing climate variability have both provided useful results. Both of these approaches will be reviewed and applied here.

This paper is intended to be a general review of interannual (ENSO and longer-term) variability in the eastern tropical Pacific and the biological and ecosystem effects of such variability. Environmental variability and effects in the ETP will be compared to what is known about more well-known systems in the North Pacific. This review, and subsequent new analyses of environmental time series, will be focused somewhat on potential impacts of environmental change on cetaceans. Consideration of this issue is part of the research mandated to the U.S. National Marine Fisheries Service by The International Dolphin Conservation Program Act of 1997 (IDCPA)².

An independent scientific peer review of this work was administered by the Center for Independent Experts located at the University of Miami. Responses to reviewer’s comments can be found in Appendix A.

¹ <http://www-mlrg.ucsd.edu/shoresta/index.html>

² http://www.nmfs.noaa.gov/prot_res/PR2/Tuna_Dolphin/IDCPA.html

ENSO VARIABILITY

The El Niño/Southern Oscillation is an irregular fluctuation involving the entire tropical Pacific Ocean and global atmosphere (Philander 1999). ENSO itself consists of an unstable interaction between surface temperature and atmospheric pressure. It results in variations in winds, rainfall, thermocline depth, circulation, and ultimately in biological productivity, and in the feeding and reproduction of fish, birds, and marine mammals. The physics of ENSO have been reviewed elsewhere (Philander 1990, Philander 1999, Wallace et al. 1998, Neelin et al. 1998) and will not be detailed here. Briefly, El Niño events occur at intervals of 2 to 7 years and are characterized by weak trade winds, a deep thermocline, and warm sea surface temperatures in the eastern equatorial Pacific. El Niño's opposite phase, La Niña, is characterized by strong trade winds, a shallow thermocline, and cool sea surface temperatures.

ENSO variability has been documented in the written record over hundreds of years (Quinn et al. 1987, Enfield 1992). It is evident in paleoclimatic records, with slight changes in amplitude or frequency, over thousands of years (Diaz and Markgraf 1992, 2000). For example, Rodbell et al. (1999) showed that the frequency of ENSO variability increased progressively over the period from about 7000 to 5000 years ago, and archaeological evidence suggests that El Niño events were either absent or very different from today for several millennia prior to that time (Sandweiss et al. 2001).

Since 1970, El Niños occurred in 1972-73, 1982-83, 1986-87, and 1997-98, with weak events in 1976-77 and 1991-92 (Fig. 3). La Niñas occurred in 1970-71, 1973-74, 1975-76, 1988-89 and 1998-99 (Larkin and Harrison 2001). Variability in the tropical Pacific was relatively low during the early 1990's, except for a weak El Niño in 1991-92. Although this period was initially interpreted as evidence of global warming, (Trenberth and Hoar 1996), it has since been interpreted as natural decadal- to centennial-scale variability (Rajagopalan et al. 1997). Latif et al. (1997) described this prolonged period of warm surface temperatures and weak trade winds as "anomalous" because the decadal mode of variability was stronger than the ENSO mode in the tropical Pacific at this time. Goddard and Graham (1997) interpreted this period as a series of 3 El Niño events that were not fully realized, due to a persistent warm patch in the central equatorial Pacific that interfered with the ocean-atmosphere interaction that normally results in oscillations between warm and cold states. Fedorov and Philander (2000) described the early 1990's as simply a period of persistent warm background conditions.

DECADAL VARIABILITY

Many global and regional studies of marine environmental time series (temperature, atmospheric pressure, winds, sea level, etc.) have been published since 1990, both to evaluate the existence of a global warming signal and to assess possible effects of climate variability on fisheries and ecosystems. For this review, "decadal"

refers to variability on a scale longer than ENSO, roughly in the range of 10 to 30 years. Although some authors use the word “interdecadal”, either as a synonym for “decadal” or to indicate the periodicity of decadal-scale regimes or phases, it will be translated to “decadal” here. In general, decadal variability in the Pacific has a smaller amplitude than ENSO variability, but there are regional exceptions to this rule. A brief review of some of these studies will show how variability in the eastern tropical Pacific compares with variability in the North Pacific at ENSO and decadal time scales. Note that variability at ENSO scales of 2-7 years is not necessarily directly related to the El Niño-Southern Oscillation.

In a typical study of global SST variability, Moron et al. (1998) found that ENSO-scale variability at periods of about 5, 4 and 2 years dominated SST variability in the Pacific during 1901-1994. While they detected longer-scale near-decadal oscillations in the Atlantic and Indian Oceans, none were statistically significant in the Pacific. This result may simply reflect the relative magnitude of variability at the two time scales. Latif et al. (1997) found that global SST variability (30°S to 60°N during 1949-1991) could be explained by three modes: ENSO (25%, strongest in the eastern equatorial Pacific), decadal (10%, strongest in a horseshoe pattern centered in the western equatorial Pacific and extending northeast and southeast), and a linear trend (or unresolved ultra-low-frequency variability). Linear trends were relatively small in the eastern tropical Pacific and did not explain much SST variability.

Several studies have found different characteristic time scales of variability for the tropical and North Pacific. Giese and Carton (1999) analyzed 1950-1993 Pacific Ocean MBT and XBT observations and concluded that ENSO variability (1-5 yrs) of surface temperature is greatest in the tropics, while decadal variability (>5 yrs) is greatest in the midlatitude North Pacific. Zhang et al. (1998b) analyzed 1950-1993 COADS data and found that ENSO variability at periods of 4 years and 2 years dominated interannual variability of SST in the tropical Pacific, but decadal variability (>5 yrs) dominated in the central North Pacific. In the tropical and North Pacific as a whole, decadal variability accounted for only one-third as much variance as did ENSO variability. An early study by Ghil and Vautard (1991) had generalized this pattern for global temperature time series: interannual oscillations (5-6 yrs) were related to global aspects of ENSO and decadal oscillations (16-21 yrs) were associated with extratropical changes.

In a longer record (1870-1999) of SST monthly anomalies in the eastern equatorial Pacific (NINO3), Mestas-Núñez and Enfield (2001) found that ENSO accounted for 79% of the total variability. The residual variability was dominated by the decadal time scale, but also included higher-frequency variability. Thus, ENSO-scale variability was much greater than longer-scale variability in this part of the ETP. For the North Pacific (>20°N), Ware (1995) found that SST variability was dominated by 20-25 year periodicity, resulting in seven warm periods and six cool periods (each ~11 years long or decadal scale) since 1850. This alternation between warm and cold phases about a decade in length is now indexed by the Pacific Decadal Oscillation (PDO), defined as the leading principal component of North Pacific monthly SST variability (Mantua et al. 1997).

Studies of global SST variability have further elaborated regional and basin-scale differences. Enfield and Mestas-Núñez (2000) performed a complex empirical orthogonal function analysis of global SST monthly anomalies from 1856 to 1991. About 45% of the

global low-passed (1.5 yr) SST variability was contained in four modes: ENSO (17%, strongest in the eastern equatorial Pacific), global warming (15%, strongest in the subtropical Pacific off California), “Pacific interdecadal” (8%, strongest in the central North Pacific), and “Atlantic multidecadal” (5%, strongest in the North Atlantic). None of the four modes were manifested to a high degree in the region of the eastern Pacific warm pool of the ETP. Similar results were found by Tomita et al. (2001), who identified seven global “centers of action” of decadal-scale variability: variability was low in the eastern Pacific warm pool, although centers of high variability are located in the central equatorial Pacific and off Peru and Baja California.

Analyses of longer time series resolve variability at scales longer than decadal, as expected. Chao et al. (2000) tentatively identified a 70-year mode in Pacific SST variability. Minobe (1997, 1999) has shown that PDO variance has two broad-band peaks at periods of 15-25 years and 50-70 years. Ware and Thomson (2000) analyzed 400-year time series of tree ring records that were assumed to represent air temperatures from the west coast of America and found three characteristic time scales: ENSO (2-8 yrs), “interdecadal” (20-40 yrs) and “multidecadal” (60-80 yrs). In this study, the ENSO cycle was the most prominent timescale, and was related to equatorial ENSO variability through both atmospheric teleconnections and coastal-trapped internal Kelvin waves. The “multidecadal” signal modulates the amplitudes and frequencies of both the ENSO and “interdecadal” signals.

Modulation of ENSO variability on the decadal time scale has been found in studies of tropical Pacific records. Mestas-Núñez and Enfield (2001) found that the late 1970’s climate shift that warmed the eastern equatorial Pacific (NINO3 region) by about 0.5°C was also characterized by increased interannual variance through the 1980’s and 1990’s (see Fig. 6c). An 1893-1994 coral record from Clipperton Atoll (within the eastern Pacific warm pool area) shows both ENSO and decadal-scale variability closely related to instrumental SOI and PDO records from recent years (Linsley et al. 2000). Reduced ENSO variability is evident between 1925 and the mid-1940’s. An and Wang (2000) found that the dominant period of SST variability in the central and eastern equatorial Pacific (NINO34 region) shifted from 3.3 years during 1967-1973 to 4.2 years during 1980-1993. Setoh et al. (1999) found a similar increase in the period of ENSO in the equatorial Pacific during the late 1970’s, but also found slight changes in the spatial pattern of the ENSO signal. However, Fedorov and Philander (2000) argued that apparent changes in ENSO may simply reflect decadal-scale changes in the background state (climatology) against which El Niño and La Niña are measured. Spectral analysis of a composite record of ENSO events since 622 A.D. showed that the period of ENSO variability has varied, within a range of 1.5 to 10 years, in cycles of 90, 50, and 23 years (Anderson 1992). None of the studies cited above found a change in ENSO variability after the late 1970’s.

The regime approach to climate variability focuses on abrupt steps rather than oscillations in climate records, although there is evidence of both types of variability (Miller et al. 1994). This approach was prompted by a remarkable 1976-1977 winter in the North Pacific: a deeper and eastward-shifted winter Aleutian low pressure system increased winds, advected warmer and moister air along the west coast of North America and colder air over the North Pacific, warmed surface waters along the west coast of North America and Alaska and cooled surface waters in the central North Pacific.

Associated changes in storm tracks, rainfall, sea ice, heat fluxes, and ocean currents were observed (Trenberth and Hurrell 1994). Ebbesmeyer et al. (1991) assembled a composite time series of 40 physical and biological variables to illustrate a distinct step-like “regime shift” in the winter of 1976-77. Clarke and Lebedev (1996) showed decadal-scale variability in equatorial Pacific trade winds, with a major weakening beginning in 1970 (before the 1976-77 North Pacific regime shift).

“Regime shift” has been a prevalent term in the literature describing and analyzing variability in North Pacific fisheries and ecosystems published during the 1990’s (cf. Francis et al. 1998, Anderson and Piatt 1999, Karl et al. 2001). However, the 1976-1977 “regime shift” is now interpreted by some a phase change in a decadal-scale oscillation lasting from about 1976 to 1988 (Trenberth and Hurrell 1994, Miller et al. 1994). Hare and Mantua (2000) analyzed 100 physical and biological time series from the northeast Pacific, covering the period 1965-1997, and found regime shifts in 1977 and 1989. The 1989 changes were not a simple reversal of the 1977 changes, and were more pronounced in the biological than in the physical time series. Ware and Thomson (2000) interpreted their 400-year time series from the “regime” point of view and showed major climate “regime shifts” (warm-to-cold as in the 1940’s or cold-to-warm as in the 1970’s) at intervals of about 30 years throughout the record. Minobe (1997) identified climate regimes of 25-35 years in North Pacific time series, with regime shifts in about 1890, 1923, 1948, and 1977. Chao et al. (2000) found a 15-20 year decadal oscillation in Pacific SST’s with phase transitions in 1924-25, 1941-42, 1957-58, and 1976-77. Biondi et al. (2001) and Gedalof and Smith (2001) extended the Pacific Decadal Oscillation record back to about 1600 with tree-ring chronologies and found pronounced decadal-scale oscillations, comparable to the 1976-77 “regime shift”, throughout the records.

The “regime” and “spectral” views of climate variability may be entirely compatible: repeated shifts between two regimes or phases at more or less regular intervals are an oscillation. Miller and Schneider (2000) concluded that “the presently limited observations cannot be used to discriminate confidently oscillatory from step-like models” of decadal variability in the North Pacific. Watanabe and Nitta (1999) showed that “the sharpness of decadal changes in 1989 [and winter 1977] arises from synchronous phase shifts of decadal variations over the Pacific Ocean and quasi-decadal variations over the North Atlantic”. Indeed, Lluch-Belda et al. (2001), in a reanalysis of long-term physical and biological variability in the California Current, used the term “trend reversal” in place of “regime shift”, to emphasize that regimes are stable trends (warming or cooling) rather than stable states (warm or cool periods). These and other authors have related biological “regimes” to the decadal climate variability summarized above (see “Biological Effects of Decadal Variability in the Pacific”).

Explanation of climate variability in the ETP is beyond the purpose of this paper. However, a few summary comments are relevant. As discussed above, ENSO is an internal cycle of the ocean-atmosphere system that has been active at periodicities of 2-7 years for at least the past 5000 years. Decadal-scale variability resembles ENSO-scale variability in spatial pattern and, like ENSO, it may involve coupled feedback between the atmosphere and ocean. Tropical and North Pacific decadal variability are negatively correlated, and forcing may occur in either direction (Pierce et al. 2000). Zhang et al. (1998a) argued that decadal variability in the tropics must be forced by extratropical decadal variability because no internal mechanism or process has been identified that

could maintain a tropical decadal oscillation. Trenberth and Hurrell (1994) concluded that atmosphere-ocean feedbacks emphasize decadal relative to interannual (ENSO) variability in the extratropics. Likewise, Giese and Carton (1999) concluded that, since “both the decadal and interannual anomaly patterns appear to result from the same basic climate phenomenon, ...ENSO is the equatorial manifestation of interannual changes in the atmospheric circulation over the entire Pacific Ocean, and decadal variability is the midlatitude manifestation”.

BIOLOGICAL EFFECTS OF ENSO VARIABILITY IN THE PACIFIC

Biological effects of recent El Niño events in the Pacific have been documented and explained primarily for phytoplankton and commercial fish stocks. Barber and Chavez (1983, 1986) and Barber et al. (1985) summarized the effects of the 1982-83 El Niño in the eastern equatorial and Peru upwelling systems: deepening of the thermocline, and thus the nutricline, resulted in decreased primary production that ultimately affected survival, reproduction, and distribution of higher trophic level organisms. Coastal upwelling continued along coastal Peru, but the thermocline was depressed below the source depth of upwelled water so that only warm, nutrient-poor waters were upwelled (Huyer et al. 1987). Nutrient depletion and reduction of phytoplankton production along the equator was even more pronounced in the 1997-98 event, but the phytoplankton community recovered in about a month after trade winds and upwelling resumed in May 1998 (Strutton and Chavez 2000). This recovery may have been in response to both resumption of local wind-driven upwelling and a shoaling of the thermocline that began in December 1997 (Chavez et al. 1999).

The 1982-83 El Niño had a variety of effects on commercial fish stocks in Peru: hake moved down the continental slope to stay in cooler deep water, shrimp and sardines moved southward so that catches in some areas decreased and in other areas increased, jack mackerel moved inshore in search of euphausiid prey and were subject to high predation mortality there, scallop abundance increased due to enhanced reproductive success in warmer water, and the anchoveta population crashed due to reduced food availability for adults and larvae. Many of these stocks recovered rapidly beginning in late 1983 (Barber and Chavez 1986).

In the eastern equatorial Pacific, sampling by ships of opportunity showed that El Niño 1982-1983 caused a deepening of the thermocline, and a reduction in chlorophyll and copepod abundance (Dessier and Donguy 1987). Dandonneau (1986), however, concluded that the winter 1982-83 reduction in the equatorial upwelling region was confined to the central equatorial Pacific and that chlorophyll remained high east of 120°W in these data. Fiedler et al. (1992) found that changes in thermocline depth and nutrient availability in the ETP resulted in a surface chlorophyll decrease during the 1986-87 El Niño and an increase during the 1988 La Niña. These changes were most pronounced in coastal and equatorial upwelling regions, but were also evident along the countercurrent thermocline ridge north of the equator.

A variety of ENSO effects have been reported on animals other than commercially-exploited fish. Changes in zooplankton biomass are often secondary to changes in species composition. For example, euphausiid species shifted distribution along southern Baja California during El Niño 1986-87, so that cold-water California

Current species were less common and warm-water tropical species were more common (Gómez-Gutiérrez et al. 1995). Zooplankton biomass off northern Chile did not change during El Niño 1997-98, although the relative abundance of small-sized copepods increased (González et al. 2000). Two Panamanian coral species were eliminated by the 1982-83 El Niño warming (Glynn and de Weerd 1991); these species were unusual in that they were highly sensitive to warming and confined to warm shallow water in a small geographic area. Warming events in the northeast Pacific, whether or not they are linked to equatorial El Niños, have changed migration patterns of bluefin tuna and sockeye salmon, increased Pacific herring recruitment, and increased body weight of mature sockeye salmon (Mysak 1986). Skipjack tuna in the western Pacific migrate zonally as the warm pool expands and contracts and optimal feeding grounds shift in response to ENSO (Lehody et al. 1997).

ENSO effects on seabirds have been relatively easy to observe at island breeding colonies. The seabird community on Christmas Island, in the central equatorial Pacific, suffered total reproductive failure from flooding rains in late 1982 and subsequent disappearance of adults due to reduced food availability, but the adults returned to breed in the following year (Schreiber and Schreiber 1984). Throughout the tropical and northeastern Pacific in 1982-83, seabird populations experienced breeding failures, mass mortalities, and migrations in search of food (Ainley et al. 1986), although a few species were not affected.

Body weight of Galapagos penguins increased during La Niña 1971 and decreased during El Niño 1972, indicating short-term response to food availability, but the population suffered 77% mortality during the 1982-83 event and had not recovered by 1997 (Dee Boersma 1998). Blue-footed booby reproductive attempts failed and breeding colonies were abandoned during the 1986-87 El Niño, apparently in response to reduced availability of sardines, but several other species were not affected (Anderson 1989). Guano-producing seabirds in coastal Peru have consistently experienced adult mortality and decreased reproductive success during El Niño events; these are short-term population effects, resulting from reduced availability of anchoveta (Tovar et al. 1987, Crawford and Jahncke 1999). All fifteen species of seabirds nesting on the Galapagos Islands stopped breeding or experienced reduced reproductive success during El Niño 1982-83, but resumed breeding the following year (Valle et al. 1987). Several seabird species experienced reduced breeding success in response to food shortage during warm-water events in the California Current (Ainley et al. 1995, Sydeman et al. 2001). Pelagic seabird surveys have shown changes in the relative abundance of less common species, but not the dominant species, during El Niño and La Niña events in the eastern equatorial Pacific (Ribic et al. 1992). Such changes may be explained by shifts in distribution between the equatorial and subtropical water masses covered by these surveys. In general, seabirds that forage in upwelling areas of the ETP and Peru Current suffer reproductive failure and mortality due to food shortage during El Niño events. However, other species that forage in areas less affected by El Niño, for example the warm pool, may be relatively unaffected (L. Ballance, pers. comm.)

Mortality or other population effects of El Niño on marine mammals has been observed in coastal ecosystems. Manzanilla (1989) observed a 1983 “El Niño mark” in the teeth of mature female Peruvian dusky dolphins and suggested that the mark resulted from low foraging success for the preferred prey, anchoveta, which became unavailable

during the 1982-83 El Niño. Consistent with this inference, no such marks were observed in other dolphin species that consume other prey. However a much lower incidence of marks in immature female and in male dusky dolphins could not be explained. Galapagos pinnipeds suffered great mortality in 1982-83, especially in younger year classes, and reduced pup production due to reduced food availability (Trillmich and Limberger 1985). Peruvian pinnipeds were affected by the reduced availability of anchoveta in 1983 (Majluf and Reyes 1989). Ramirez (1986) observed diet changes and reduced feeding success of Bryde's whales off Peru during El Niño 1982-83.

Shane (1995) argued that the reduced availability of squid around Santa Catalina Island during the 1982-83 El Niño triggered a competitive displacement of pilot whales by Risso's dolphins. ENSO variability has had short-term effects on pup production and adult distribution of central California pinnipeds, probably through food availability, but no long-term population effects (Sydeman and Allen 1999). These authors, in fact, concluded that oceanographic effects "do not appear to confound interpretations of population recovery". However, El Niño reductions in prey availability have caused reduced pup production and increased pup mortality at southern California Channel Island pinniped breeding colonies; the severe 1982-83 and 1997-98 events also caused juvenile and adult mortality resulting in population changes lasting several years and temporary interruption of the long-term recovery of depleted populations (DeLong and Melin 2000).

Large whales are able to move in response to El Niño perturbations. An unusual coccolithophore bloom in the Bering Sea during El Niño 1997-98 was exploited by zooplankton and baleen whales that moved onto the middle shelf to feed on the krill (Tynan 1999). El Niño warming inhibits migration of gray whales to southernmost Baja California calving grounds, but the whales continue to utilize more northern areas (Gardner and Chávez-Rosales 2000).

A generalization about ENSO effects on higher organisms was made by Sharp (1992): "Close examination of the facts has shown that the effects of individual El Niño events can be devastating, but within a short time, the majority of the effects fade, and life goes on. El Niño/Southern Oscillation (ENSO) cycles are perturbations of the most important global climate pattern, the seasonal cycle. Ocean and atmosphere are sufficiently interactive on daily, seasonal, and interannual bases that ocean inhabitants have had to adopt responsive survival strategies into their life histories to cope with these frequent environmental processes [and] to persist." An unusual example of such an adaptive response is the ability of Galapagos marine iguanas to shrink in body size, and thus increase energy efficiency, to compensate for El Niño reductions in food availability (Wikelski and Thom 2000).

BIOLOGICAL EFFECTS OF DECADEAL VARIABILITY IN THE PACIFIC

Biological effects of decadal-scale climate variability have been observed and explained, but only when time series from commercial fisheries or exceptionally long research programs are available. Data collected in California coastal waters for the CalCOFI program, since 1949, have shown interannual variability of physical and biological variables that is at least as great as seasonal variability. Interannual ENSO-scale variability of zooplankton biomass appears to be driven by variations in transport

from the north (McGowan et al. 1996). In contrast, a 70% decrease in macrozooplankton biomass and a surface layer warming of up to 1.5°C from 1951 to 1993 off southern California has been explained by internal processes (Roemmich and McGowan 1995). Increased stratification has inhibited upwelling and mixing of deep water, and thus local productivity within the system. McGowan et al. (1998) lamented that “the role of climatic variation in regulating marine populations and communities is not well understood... probably because of the mismatch between the scales of important atmospheric and oceanographic processes and the spatial and temporal dimensions of biological research programs.”

Yet, studies reviewed below have demonstrated population effects of climate variability. Most of these studies view climate variability in terms of regimes, because variability of North Pacific stocks and ecosystems was initially described in terms of biological regimes in the 1990's.

North Pacific ocean climate changes in 1977 (intensified Aleutian Low) and 1989 (back near-average Aleutian Low, Hare and Mantua 2000) affected the abundance and ocean survival of salmon, the distribution and spawning behavior of hake and sardine, and recruitment of several groundfish species in the eastern North Pacific (McFarlane et al. 2000). Beamish et al. (1999) argue that these climate regime shifts and accompanying fluctuations in fish stocks have been occurring since at least 1600. Hollowed et al. (2001) reviewed time series of catch and recruitment for Northeast Pacific fish stocks and found evidence that some stocks were affected by 1976-77 and 1988-89 phase changes in the Pacific Decadal Oscillation, but that others were positively affected by ENSO-scale warm conditions on the eastern side of the North Pacific (“Niño North”).

Decadal-scale variability of the Aleutian Low affected recruitment of Japanese sardine and can explain variability of catch back to 1600 (Yasuda et al. 1999). Declines of both the Japanese and California sardine stocks during the 1940's were caused by long-term cooling of surface waters (Lluch-Belda et al. 1989). Recovery of California and Peru stocks during the 1970's was related to warming through effects on spawning (Lluch-Belda et al. 1992). Lluch-Cota et al. (1997) combined catch records of Pacific sardine and anchovy stocks into a composite “regime indicator series” and identified three regimes in the period 1925-1995, with regime shifts around 1950 and in the late 1970's. Then, using the spectral approach, they showed that the sardine/anchovy regime series is related to global decadal climate variability of surface air temperature.

Francis et al. (1998) reviewed ecosystem effects of the 1976-77 shift in atmospheric dynamics over the northeast Pacific and concluded that phytoplankton, zooplankton, and fish production all responded to this change, resulting in substantial ecosystem “reorganization”. However, the magnitude and even the sign of the response differed between regions. For example, zooplankton biomass increased in the central subarctic Pacific (Brodeur and Ware 1992, Brodeur et al. 1996), but decreased off Southern California (Roemmich and McGowan 1995) and did not change substantially off Baja California (Lavaniegos et al. 1998). The strongest and most rapid effects appeared at lower trophic levels, although responses were observed at all levels (marine mammals, fish and birds as well as phytoplankton and zooplankton).

Anderson and Piatt (1999) showed a similar reorganization of the community structure of nekton and their predators in the Gulf of Alaska ecosystem after the late 1970's climate shift: forage species declined and groundfish increased, with negative

effects on piscivorous birds and marine mammals. Changes in zooplankton biomass in the subarctic Pacific affected production of nekton, several salmon stocks, and forage availability for birds and mammals (Brodeur et al. 1996; Francis et al. 1998). Effects on salmon occurred in early life history (first year of life in ocean, Francis et al. 1998) and at spawning (Downton and Miller 1998).

Sydeman et al. (2001) found interannual changes in reproductive success and diet of several species of seabirds breeding in the California Current system during 1969-1997. However, in contrast to the findings of pervasive ecosystem effects of a late 1970's North Pacific climate shift, only 2 of 11 species showed changes related to a regime shift and these changes occurred in the late 1980's.

Polovina et al. (1995) reviewed decadal variability in wind mixing and resulting changes in primary and secondary production in the subtropical and subarctic North Pacific during the late 1970's. They found that the ecosystem response was different for systems with nutrient- and light-limited phytoplankton production. In the central North Pacific, total chlorophyll increased when stronger and more frequent wind mixing led to greater nutrient input (Venrick et al. 1987). Productivity of the ecosystem at all levels increased, but then decreased when the wind patterns relaxed in the late 1980's (Polovina et al. 1994).

Biological changes cannot always be clearly attributed to ENSO or decadal climate variability. For example, a persistent reduction in zooplankton biomass along the coast of Peru that occurred in the mid-1970's may have been related to the 1972-73 El Niño (Carrasco and Lozano 1989). Muck (1989) argued that changes in zooplankton, fish, and predators in the Peru Current ecosystem at this time were all related to the collapse of the anchoveta stock, which was caused by a combination of overfishing and El Niño 1972-73.

Mechanistic explanations of biological effects of climate change have been proposed. For example, decreased upwelling in the California Current system (Bakun 1990) resulted in decreased availability of the euphausiid *Thysanoessa spinifera*, a preferred prey species, and reduced abundance of Cassin's auklet in the 1980's (Ainley et al. 1996). A 90% decline in sooty shearwater abundance off southern California from 1987 to 1994, concurrent with a long-term warming, was explained by decreased zooplankton abundance in the inshore feeding grounds (Veit et al. 1996). Ware and Thomson (1991) showed that sardine and hake biomass off the west coast of North America decreased by a factor of 5 during 1916-1942 and found evidence that a strong relaxation in wind-driven upwelling led to lower primary production and thus lower larval survival and recruitment. Polovina (1996) presented evidence that increased sardine abundance off Japan in 1977 resulted in a lower proportion of juvenile bluefin tuna migrating from the western to eastern Pacific.

EASTERN TROPICAL PACIFIC DECADEAL VARIABILITY AND TRENDS

Long time series of physical or biological variables are not available for the eastern tropical Pacific, with the exception of the NINO SST monthly series for equatorial surface waters. The NINO3 eastern equatorial Pacific area abuts the eastern Pacific warm pool, but as illustrated elsewhere in this paper, variability in these two areas differs in magnitude, timing, and spectral distribution. Short but accurate 22-year regional

time series were derived from monthly data fields produced by the NOAA/NWS National Center for Environmental Prediction's Ocean Data Assimilation System (NCEP, Behringer et al. 1998). NCEP uses a dynamic ocean model, driven by observed wind stress and surface heat fluxes, to assimilate sparse temperature observations. The observations constrain the model, while at the same time the model interpolates across data gaps using the physics of the model ocean. Surface temperature and thermocline depth (20°C isotherm depth in the tropics) were extracted from the resulting three-dimensional temperature fields and averaged over four regions (Fig. 4): (1) ETP warm pool area (5-20°N, east of 120°W), (2) NINO3 eastern equatorial Pacific (5°S-5°N, 90-150°W), (3) California Current (30-39°N, out to ~300km from the coast), and (4) central North Pacific (30-45°N, 165°E-165°W).

Time series of monthly anomalies of surface temperature and thermocline depth were calculated to remove seasonal variability and emphasize interannual and longer-scale variability (Fig. 5). ENSO-scale variability is dominant in the ETP, with major El Niño events (warm surface temperatures and deep thermoclines) in 1982-1983 and 1997-1998 and weaker events in 1986-1987 and 1991-1992. A major La Niña event (cool surface temperatures and shallow thermoclines) occurred in 1987-1988 and weaker events in 1984-1985 and 1998-1999. In general, ENSO anomalies in the ETP warm pool area are about half the magnitude and several months later than anomalies along the equator. Most ENSO events, but not all (e.g. 1986-87, Lenarz et al. 1995), appear in the California Current. The central North Pacific shows moderate ENSO-scale variability, but anomalies there are of opposite sign than corresponding anomalies in the ETP and California Current.

Cumulative sums of the surface temperature and thermocline depth anomaly time series are presented to visualize the longer-term characteristics of the series. Cumulative sums are used in industrial quality control to detect small and sustained shifts in processes (Manly and Mackenzie 2000), and have been used to detect climate or regime shifts (Yáñez et al. 1992, Beamish et al. 1999). Climate shifts are marked by changes in slope of the cumulative sum plot. Cumulative sums of the four NCEP surface temperature (Fig. 5b) and thermocline depth (Fig. 5d) time series show evidence of a climate shift in the North Pacific and in the California Current around 1990 (Hare and Mantua, 2000). The ETP warm pool and NINO3 series are dominated by ENSO variability. The only obvious longer-term feature in the two ETP series is the relatively constant period from 1990-1995. No climate shifts comparable to 1967-77 (or ~1990 in the North Pacific) are apparent in the 1980-2001 ETP series.

Linear trends of surface temperature in the 1980-2001 time series were not statistically significant, except for post-1997 in the central North Pacific (Table 1). Linear trends of thermocline depth in the ETP are statistically significant, indicating an overall shoaling of the thermocline of 7.8m in the eastern equatorial Pacific and 6.1m in the ETP warm pool since 1980. However, these trends are very sensitive to the length of the series: trends for 1980-1998, before the moderate La Niña conditions in 1999-2001, are not significant, and trends for 1984-1998 indicate significant deepening of the ETP thermocline. Thus, it is not possible to meaningfully describe linear trends during the 1980-2001 period; ENSO variability predominated.

Reconstructed SST time series cover longer periods than series based only upon instrumental observations. SST monthly anomaly time series since 1901 show ENSO-

scale variability (Fig. 6a); climate shifts are evident when the series are viewed as cumulative sums (Fig. 6b). The 1976-77 climate shift is evident in the ETP and North Pacific, although the changes in slope are much greater in the North Pacific than in the ETP. At this time, long-term warming begins in the ETP and California Current, while cooling begins in the central North Pacific. Hare and Mantua (2000) calculated 1976-1977 decadal sea surface temperature shifts by differencing 1965-1976 and 1977-1988 means: warmings of +0.6 to +1°C occurred along the Pacific coast of North America from California to the Bering Sea, while coolings of -0.8 to -1°C occurred in much of the central North Pacific. Calculation of 1976-1977 decadal changes using regional GISST data show similar changes in the North Pacific (+0.57°C in the California Current and -0.50°C in the central North Pacific), but considerably lesser warmings in the tropical Pacific (+0.33°C in the NINO3 region and +0.15°C in the ETP core area).

The 1989 climate shift is apparent only in the North Pacific, although a slight change in slope for the California Current occurs in the early 1990's. Similarly, the prolonged warm period of the early 1990's in the ETP results in a slight change in slope. In general, the cumulative sums show a prevalence of warm and cool periods of 2-3 years associated with ENSO events in the ETP, and longer warming and cooling trends in the North Pacific corresponding to decadal-scale variability. The NINO3 series in Fig. 6a also shows an apparent change in the frequency and amplitude of ENSO variability in the mid-1970's (An and Wang 2000). The change in ENSO amplitude is illustrated by the increased 10-year variance in NINO3 SST monthly anomalies after the late 1960's (Fig. 6c), for which there is no corresponding change in the ETP warm pool.

Time series of other tropical Pacific, North Pacific, and global climate indices are plotted in Fig. 7. NINO3, TNI, and PDO are temperature indices. SOI, NPI, and NOI are atmospheric pressure indices. GAAM is a global index representing the overall "rotation" of the Earth's atmosphere; interannual changes in GAAM result from variations in trade winds, westerlies, and jet-streams associated with ENSO and other global-scale climate changes (Salstein and Rosen 1984). All of these climate indices underwent a shift in the winter of 1976-77. The late 1980's climate shift in the North Pacific (Hare and Mantua 2000) is not evident in any of the series in Fig. 7, but is evident in the Central North Pacific SST series (Fig. 6b). No climate shift is evident in the tropical Pacific since 1976-77, although it is possible that a 1998-99 shift is as yet unresolved with only 3-4 years of observations to the present time (Schwing and Moore 2000). As El Niño returns in 2002, ENSO continues to dominate interannual variability in the ETP.

A recent paper (McPhaden and Zhang 2002) presented evidence that sea surface warming in the equatorial Pacific since the 1970's is associated with a decrease in equatorial upwelling that is part of the meridional overturning circulation forced by easterly trade winds. The authors suggest that the reduction in upwelling should also affect biological production in the region. Time series of zonal trade wind strength since 1948 show weakening during the 1970's (Fig. 8), with a greater change in the central equatorial Pacific than in the eastern equatorial Pacific (winds are more easterly in the central and more southerly in the eastern equatorial Pacific, with mean zonal components of -5.29 and -2.66 m s⁻¹ respectively). Long time series of phytoplankton biomass or productivity in the equatorial Pacific are not available, or have not been published. Available satellite and shipboard data indicate that phytoplankton biomass has not changed in the central equatorial Pacific, has decreased slightly in the eastern equatorial

Pacific since the end of the 1980's, and has actually increased in the warm pool of the ETP (Gregg and Conkright 2002, Fig. 8).

CONCLUSION

The studies reviewed above show that oceanographic variability occurs in the ETP and North Pacific at both ENSO (2-7 years) and decadal (10-30 years) scales. ENSO-scale variability predominates in the ETP, and appears in the North Pacific with some delay and attenuation. Decadal-scale variability predominates in the North Pacific, although some decadal-scale changes are evident in the ETP. This review has been limited to a description of such variability, and has not considered theory or mechanisms, because it was motivated by a need to examine possible effects of environmental change on dolphin stocks in the ETP. The eastern equatorial Pacific (NINO3, Fig. 4) corresponds to the southern portion of the area in which the U.S. National Marine Fisheries Service and the Interamerican Tropical Tuna Commission monitor dolphin abundance and manage a yellowfin tuna fishery. The ETP warm pool area covers the distribution of two depleted dolphin stocks: northeastern offshore spotted dolphins and eastern spinner dolphins.

ENSO variability has been shown to affect fish, birds, pinnipeds, and cetaceans. Almost all observations of such environmental effects have been on coastal or island populations. While it is true that ENSO effects are more extreme in highly productive coastal environments, other factors may be important. Perhaps such populations are less adaptable or opportunistic. Certainly, these populations are more readily accessible for long-term study. El Niño events often cause changes in distribution of species as the distribution of preferred water masses and prey changes. Population effects are observed on local breeding grounds, but recovery usually occurs rapidly when the El Niño event is over. Effects of El Niño on distribution of dolphins in the ETP were recognized by Gerrodette et al. (1998) in planning recent dolphin abundance surveys. They compared maps of encounter rates from tuna vessels (1975-96) and research vessels (1982-93) for El Niño and non-El Niño years. Both eastern spinner and offshore spotted dolphins showed slight expansions of range during El Niño years, but there was no indication of movement out of the survey area.

Population effects of ENSO on ETP dolphins have not been detected. In experiments with an ecosystem model, dolphin populations are insensitive to ENSO-scale variability because of their low turnover rate and diet of abundant mesopelagic fish (Watters et al.³). In the real world, the long life spans, iteroparity, and low reproductive rates of these K-selected species, and their generalized feeding habits, probably reduce dolphin population responses to moderate changes on seasonal and ENSO time scales.

There is no evidence of environmental change, in the sense of a decadal-scale climate shift, in the ETP since 1977. The 22-year surface temperature and thermocline depth series (Fig. 6) are too short to make meaningful inferences about decadal variability or long-term climate change. With the caveat about the length of these series, the

³ Watters GM, Olson RJ, Francis RC, Fiedler PC, Polovina JJ, Reilly SB, Aydin KY, Boggs CH, Essington TE, Walters CJ, Kitchell JF (in prep) Physical forcing and the dynamics of the pelagic ecosystem in the eastern tropical Pacific: simulations with ENSO-scale and global-warming climate drivers.

following question can be asked: Is it likely that temperature changes of a few tenths of a degree or thermocline depth changes of a few meters could have an effect on dolphin stocks in the ETP? A definitive answer to this question will require observational and modeling studies of dolphin feeding and reproduction. Such changes are small relative to seasonal and ENSO variability, and it is possible that they would not have an important effect. Evidence that dolphins feed on prey aggregated near the thermocline suggests that thermocline shoaling might increase prey availability (Fiedler et al. 1998).

Although the 1976-77 climate shift was not a unique change in the North Pacific environment, it was of exceptional magnitude. Stephens et al. (2001) showed that the mid-1970's shift in Pacific upper ocean temperature was a basin-wide warming that continued through 1998 with no signs of returning to a cooler phase. Since the end of the 1997-98 El Niño, however, there has been speculation about a winter 1998-1999 regime shift (Hare and Mantua 2000, Schwing and Moore 2000, Peterson and Mackas 2001, Minobe 2002). As of May 2000, the consensus of scientists working in the California Current was that the system was in a third straight La Niña year and that data did "not yet support the idea of a climate regime shift" (Durazo et al. 2001). The question of whether recent changes in the North Pacific are a climate regime shift is not yet decided and continues to be discussed at scientific meetings (e.g. PICES X Annual Meeting, October 2001; CalCOFI Conference 2001, November).

The magnitude of a climate signal cannot be assumed to affect a biological response in a linear fashion (Hunt et al. 2002). The SST time series in Fig. 6 and other environmental time series in Fig. 7 indicate that the 1976-77 climate shift in the eastern equatorial Pacific was less than half the magnitude it was in the North Pacific. The change was even smaller in the warm pool area of the ETP. It is possible that population and ecosystem changes were induced in the ETP, as they were in the California Current and Gulf of Alaska, but there is no observational evidence of such changes. The long-term change that occurred in the ETP in the late 1970's was less than typical interannual changes associated with ENSO variability (Fig. 9). However, the persistence of such a low-amplitude change may be important to organisms and populations adapted to intense ENSO-scale variability.

Studies of environmental variability and change in recent years have often been carried out to resolve effects of human-induced factors such as overfishing or global warming. Fisheries scientists have recognized since the early 1990's that environmental variability is at least as important as fishing mortality or other anthropogenic factors in forcing variability of fish stocks (Southward et al. 1988, Sharp and McLain 1993). However, the U.N. Intergovernmental Panel on Climate Change has consistently emphasized that potential impacts of climate variability or climate change are likely to exacerbate, rather than replace, existing human stresses on fisheries (Everett et al. 1996, Burkett et al. 2001). In the case of dolphins and other marine mammals, life history traits that may have evolved in part as an adaptive response to cyclic perturbations such as ENSO (long life spans, slow growth rates, late maturity, and relatively few young), also render them vulnerable to excessive human-induced or other population reductions (Musick 1999, Fair and Becker 2000). Interaction between natural variability and human intervention must be considered in management decisions.

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LITERATURE CITED

- Ainley, D. G., Carter, H. R., Anderson, D. W., Briggs, K. T., Coulter, M. C., Cruz, F., Cruz, J. B., Valle, C. A., Fefer, S. I., Hatch, S. A., Schreiber, E. A., Schreiber, R. W., Smith, N. G. 1986. Effects of the 1982-83 El Niño-Southern Oscillation on Pacific Ocean bird populations. In Onelet H (ed) Proc XIX International Ornithological Congress, National Museum of Natural Sciences, Ottawa, 1747-1756.
- Ainley, D. G., Sydeman, W. J., Norton, J. 1995. Upper trophic level predators indicate interannual negative and positive anomalies in the California Current food web. *Mar. Ecol. Prog. Ser.* 118:69-79.
- Ainley, D. G., Spear, L. B., Allen, S. G. 1996. Variation in the diet of Cassin's auklet reveals spatial, seasonal, and decadal occurrence patterns of euphausiids off California, USA. *Mar. Ecol. Prog. Ser.* 137: 1-10.
- An, S-I., Wang, B. 2000. Interdecadal change of the structure of the ENSO mode and its impact on the ENSO frequency. *J. Clim.* 13:2044-2055.
- Anderson, D. J. 1989. Differential responses of boobies and other seabirds in the Galápagos to the 1986-87 El Niño-Southern Oscillation event. *Mar. Ecol. Prog. Ser.* 52: 209-216.
- Anderson, R.Y. 1992. Long-term changes in the frequency of occurrence of El Niño events. In Diaz HF and Markgraf V (eds) *El Niño: historical and paleoclimatic aspects of the southern oscillation*. University Press, Cambridge. 193-200.
- Anderson, P. J., Piatt, J. F. 1999. Community reorganization in the Gulf of Alaska following ocean climate regime shift. *Mar. Ecol. Prog. Ser.* 189:117-123.
- Bakun, A. 1990. Global climate change and intensification of coastal ocean upwelling. *Science* 247:198-201.
- Barber, R. T., Chavez, F. P. 1983. Biological consequences of El Niño. *Science* 222:1203-1210.
- Barber, R. T., Chavez, F. P., Kogelschatz, J. E. 1985. Biological effects of El Niño. *Bol ERFEN* 14:3-29.
- Barber, R. T., Chavez, F. P. 1986. Ocean variability in relation to living resources during the 1982-83 El Niño. *Nature*. 319:279-285.
- Beamish, R. J., Noakes, D. J., McFarlane, G. A., Klyashtorin, L., Ivanov, V. V., Kurashov, V. 1999. The regime concept and natural trends in the production of Pacific salmon. *Can. J. Fish. Aquat. Sci.* 56:516-526.

- Behringer, D. W., Ji, M., Leetmaa, A. 1998. An improved coupled model for ENSO prediction and implications for ocean initialization. Part I: the ocean data assimilation system, *Mon. Weather Rev.* 126:1013-1021.
- Biondi, F., Gershunov, A., Cayan, D. R. 2001. North Pacific decadal climate variability since 1661. *J. Climate* 14:5-10.
- Brodeur, R. D., Ware, D. M. 1992. Long-term variability in zooplankton biomass in the subarctic Pacific Ocean. *Fish. Oceanogr.* 1:32-38.
- Brodeur, R. D., Frost, B. W., Hare, S. R., Francis, R. C., Ingraham, W. J. 1996. Interannual variations in zooplankton biomass in the Gulf of Alaska, and covariation with California Current zooplankton biomass. *CalCOFI Rep.* 37:80-99.
- Burkett, V., Codignotto, J. O., Forbes, D. L., Mimura, N., Beamish, R. J., Ittekkot, V. 2001. Coastal Zones and Marine Ecosystems. In: McCarthy, J. J., Canziani, O. F., Leary, N. A., Dokken, D. J., White, K. S. (eds) *Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge and New York, pp. 347-379.
- Carrasco, S., Lozano, O. 1989. Seasonal and long-term variations of zooplankton volumes in the Peruvian Sea, 1964-1987. In: Pauly, D., Muck, P., Mendo, J., Tsukayama, I. (eds) *The Peruvian upwelling system: dynamics and interactions, ICLARM Conference Proceedings*, p. 82-85.
- Chao, Y., Ghil, M., McWilliams, J. C. 2000. Pacific interdecadal variability in this century's sea surface temperatures. *Geophys. Res. Lett.* 27:2261-2264.
- Chavez, F. P., Strutton, P. G., Friederich, G. E., Feely, R. A., Feldman, G. C., Foley, D. G., McPhaden M. J. 1999. Biological and chemical response of the equatorial Pacific Ocean to the 1997-98 El Niño. *Science* 286:2126-2131.
- Clarke, A. J., Lebedev, A. 1996. Long-term changes in the equatorial Pacific trade winds. *J. Climate* 9:1020-1029.
- Conkright, M. E., Antonov, J. I., Baranova, O., Boyer, T. P., Garcia, H. E., Gelfeld, R., Johnson, D., Locarnini, R. A., Murphy, P. P., O'Brien, T. D., Smolyar, I., Stephens, C. 2002. *World Ocean Database 2001, volume 1: introduction.* NOAA Atlas NESDIS 42. U. S. Government Printing Office, Washington.
- Crawford, R. J. M., Jahncke, J. 1999. Comparison of trends in abundance of guano-producing seabirds in Peru and southern Africa. *S. Afr. J. Marine Sci.* 21:145-156.
- Dandonneau, Y. 1986. Monitoring the sea surface chlorophyll concentration in the tropical Pacific: consequences of the 1982-83 El Niño. *Fish B - NOAA* 84:687-695.

- Dee Boersma, P. 1998. Population trends of the Galápagos penguin: impacts of El Niño and La Niña. *Condor* 100:245-253.
- Delcroix, T. 1993. Seasonal and interannual variability of sea surface temperatures in the tropical Pacific, 1969-1991. *Deep-Sea Res. Pt. I* 40:2217-2228.
- DeLong, R. L., Melin, S. R. 2000. Thirty years of pinniped research at San Miguel Island. In: Browne, D. R., Mitchell, K. L., Chaney, H. W. (eds) *Fifth California Islands Symposium*, U. S. Department of the Interior, Minerals Management Service, p. 401-406.
- Dessier, A., Donguy, J. R. 1987. Response to El Niño signals of the epipelagic copepod populations in the eastern tropical Pacific. *J. Geophys. Res. - Oceans* 92:14,393-14,403.
- Diaz, H. F., Markgraf, V. (eds) 1992. *El Niño: historical and paleoclimatic aspects of the Southern Oscillation*. Cambridge University Press, Cambridge.
- Diaz, H. F., Markgraf, V. (eds) 2000. *El Niño and the Southern Oscillation: multiscale variability and global and regional impacts*. Cambridge University Press, Cambridge.
- Downton, M. W., Miller, K. A. 1998. Relationships between Alaska salmon catch and North Pacific climate on interannual and interdecadal time scales. *Can. J. Fish. Aquat. Sci.* 55:2255-2265.
- Durazo, R., Baumgartner, T. R., Bograd, S. J., Collins, C. A., de la Campa, S., García, J., Gaxiola-Castro, G., Huyer, A., Hyrenbach, K. D., Loya, D., Lynn, R. J., Schwing, F. B., Smith, R. L., Sydeman, W. J., Wheeler, P. 2001. The state of the California Current, 2000-2001: a third straight La Niña year. *CalCOFI Rep.* 42:29-60.
- Ebbesmeyer, C. C., Cayan, D. R., McLain, D. R., Nichols, F. H., Peterson, D. H., Redmond, K. T. 1991. 1976 step in the Pacific climate: forty environmental changes between 1968-1975 and 1977-1984. In: Betancourt, J. L., Tharp, V. L. (eds) *Proceedings of the Seventh Annual Pacific Climate (PACCLIM) Workshop*, April 1990. Calif. Dep. Water Resour. Interagency Ecol. Stud. Program Tech. Rep. 26:115-126.
- Enfield, D. B. 1992. Historical and prehistorical overview of El Niño/Southern Oscillation. In Diaz, H. F., Markgraf, V. (eds) *El Niño and the Southern Oscillation: multiscale variability and global and regional impacts*. Cambridge University Press, Cambridge, 95-117.
- Enfield, D. B., Mestas-Núñez, A. M. 2000. Global modes of ENSO and non-ENSO SST variability and their associations with climate. In: Diaz, H. F. and V. Markgraf (eds.) *El Niño and the Southern Oscillation: Multiscale Variability and Global and Regional Impacts*, Cambridge University Press, p. 89-112.

- Everett, J. E., Krovnin, A., Lluch-Belda, D., Okemwa, E., Regier, H. A., Troadec, J. P. 1996. Fisheries. In: Watson, R. T., Zinyowera, M. C., Moss, R. H. (eds) Climate Change 1995: Impacts, Adaptations and Mitigations of Climate Change: Scientific-Technical Analyses. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York, p. 511-537.
- Fair, P. A., Becker, P. R. 2000. Review of stress in marine mammals. J. Aquatic Ecosystem Stress and Recovery 7:335-354.
- Fedorov, A. V., Philander, S. G. 2000. Is El Niño changing? Science 288:1997-2002.
- Fiedler, P. C., Chavez, F. P., Behringer, D. W., Reilly, S. B. 1992. Physical and biological effects of Los Niños in the eastern tropical Pacific, 1986-1989. Deep-Sea Res. 39:199-219.
- Fiedler, P. C., Barlow, J., Gerrodette, T. 1998. Dolphin prey abundance determined from acoustic backscatter data in eastern Pacific surveys. Fish B - NOAA 96:237-247.
- Fiedler, P. C., Philbrick, V. A. 2002. Environmental change in the eastern tropical Pacific Ocean: Observations in 1986-1990 and 1998-2000. Administrative Report No. LJ-02-15, NMFS, Southwest Fisheries Science Center, 8604 La Jolla Shores Drive, La Jolla, CA 92037.
- Francis, R. C., Hare, S. R., Hollowed, A. B., Wooster, W. S. 1998. Effects of interdecadal climate variability on the oceanic ecosystems of the NE Pacific. Fish. Oceanogr. 7:1-21.
- Gagan, M. K., Ayliffe, L. K., Beck, J. W., Cole, J. E., Druffel, E. R. M., Dunbar, R. B., Schrag, D. P. 2000. New views of tropical paleoclimates from corals. Quat. Sci. Rev. 19:45-64.
- Gardner, S. C., Chávez-Rosales, S. 2000. Changes in the relative abundance and distribution of gray whales (*Eschrichtius robustus*) in Magdalena Bay, Mexico during an El Niño event. Mar. Mammal Sci. 16:728-738.
- Gedalof, Z., Smith, D. J. 2001. Interdecadal climate variability and regime-scale shifts in Pacific North America. Geophys. Res. Lett. 28:1515-1518.
- Gerrodette, T., Olson, P., Kinzey, D., Anganuzzi, A., Fiedler, P., Holland, R. 1998. Report of the survey design meeting for estimating abundance of eastern tropical Pacific dolphins, 1998-2000: December 17-18, 1997. Administrative Report No. LJ-98-03, NMFS, Southwest Fisheries Science Center, 8604 La Jolla Shores Drive, La Jolla, CA 92037. 25 pp.
- Ghil, M., Vautard, R. 1991. Interdecadal oscillations and the warming trend in global temperature time series. Nature 350:324-327.

- Giese, B. S., Carton, J. A. 1999. Interannual and decadal variability in the tropical and midlatitude Pacific Ocean. *J. Clim.* 12:3402-3418.
- Gregg, W. W., Conkright, M. E. 2002. Decadal changes in global ocean chlorophyll. *Geophys. Res. Lett.* in press.
- Glynn, P. W., de Weerd, W. H. 1991. Elimination of two reef-building hydrocorals following the 1982-83 El Niño warming event. *Science* 253:69-71.
- Goddard, L., Graham, N. E. 1997. El Niño in the 1990s. *J. Geophys. Res. - Oceans* 102:10,423-10,436.
- Gómez-Gutiérrez, J., Palomares-García, R., Gendron, D. 1995. Community structure of the euphausiid populations along the west coast of Baja California, Mexico, during the weak ENSO 1986-1987. *Mar. Ecol. Prog. Ser.* 120:41-51.
- González, H. E., Sobarzo, M., Figueroa, D., and Nöthig, E-M. 2000. Composition, biomass and potential grazing impact of the crustacean and pelagic tunicates in the northern Humboldt Current area off Chile: differences between El Niño and non-El Niño years. *Mar. Ecol. Prog. Ser.* 195:201-220.
- Hare, S. R., Mantua, N. J. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. *Prog. Oceanogr.* 47:103-145.
- Hollowed, A. B., Hare, S. R., Wooster, W. S. 2001. Pacific Basin climate variability and patterns of Northeast Pacific marine fish production. *Prog. Oceanogr.* 49:257-282.
- Hunt, G. L., Stabeno, P., Walters, G., Sinclair, E., Brodeur, R. D., Napp, J. M., Bond, N. A. 2002. Climate change and control of the southeastern Bering Sea ecosystem. *Deep-Sea Res. Pt. II* 49:in press.
- Huyer, A., Smith, R. L., Paluszkievicz, T. 1987. Coastal upwelling off Peru during normal and El Niño times, 1981-1984. *J. Geophys. Res. - Oceans* 92:14,297-14,307.
- Karl, D. M., Bidigare, R. R., Letelier, R. M. 2001. Long-term changes in plankton community structure and productivity in the North Pacific Subtropical Gyre: the domain shift hypothesis. *Deep-Sea Res. Pt. II* 48: 1449-1470.
- Larkin, N. K., Harrison, D. E. 2001. Tropical Pacific ENSO cold events, 1946-95: SST, SLP, and surface wind composite anomalies. *J. Clim.* 14:3904-3931.
- Latif, M., Kleeman, R., Eckert, C. 1997. Greenhouse warming, decadal variability, or El Niño? An attempt to understand the anomalous 1990s. *J. Clim.* 10:2221-2239.

- Lavaniegos, B. E., Gómez-Gutiérrez, J., Lara-Lara, J. R., Hernández-Vázquez, S. 1998. Long-term changes in zooplankton volumes in the California Current System - the Baja California region. *Mar. Ecol. Prog. Ser.* 169:55-64.
- Lehodey, P., Bertignac, M., Hampton, J., Lewis, A., Picaut, J. 1997. El Niño Southern Oscillation and tuna in the western Pacific. *Nature* 389:715-718.
- Lenarz, W. H., Ventresca, D. A., Graham, W. M., Schwing, F. B., Chavez, F. 1995. Explorations of El Niño events and associated biological population dynamics off central California. *CalCOFI Rep.* 36:106-119.
- Linsley, B. K., Ren, L., Dunbar, R. B., Howe, S. S. 2000. El Niño Southern Oscillation (ENSO) and decadal-scale climate variability at 10°N in the eastern Pacific from 1893 to 1994: A coral-based reconstruction from Clipperton Atoll. *Paleoceanography* 15:322-335.
- Lluch-Belda, D., Crawford, R. J. M., Kawasaki, T., MacCall, A. D., Parrish, R. H., Schwartzlose, R. A., Smith, P. E. 1989. World-wide fluctuations of sardine and anchovy stocks: the regime problem. *S. Afr. J. Mar. Sci.* 8:195-205.
- Lluch-Belda, D., Lluch-Cota, D. B., Hernández-Vázquez S., Salinas-Zavala C. A. 1992. Sardine population expansion in eastern boundary systems of the Pacific Ocean as related to sea surface temperature. *S. Afr. J. Mar. Sci.* 12:147-155.
- Lluch-Belda, D., Laurs, R. M., Lluch-Cota, D. B., Lluch-Cota, S. E. 2001. Long-term trends of interannual variability in the California Current system. *CalCOFI Rep.* 42:129-144.
- Lluch-Cota, D. B., Hernández-Vázquez, S., Lluch-Cota, S. E. (1997) Empirical investigation on the relationship between climate and small pelagic global regimes and El Niño-Southern Oscillation (ENSO). *FAO Fisheries Circular No.* 934
- Majluf, P., Reyes, J. C. 1989. The marine mammals of Peru: a review. In: Pauly, D., Muck, P., Mendo, J., Tsukayama I (eds) *The Peruvian upwelling system: dynamics and interactions*, ICLARM Conf Proc 18, p 344-363
- Manly, B. F. J., Mackenzie, D. 2000. A cumulative sum type of method for environmental monitoring. *Environmetrics* 11:151-166.
- Mann, M. E., Gille, E., Bradley, R. S., Hughes, M. K., Overpeck, J., Keimig, F. T., Gross, W. 2000. Global temperature patterns in past centuries: An interactive presentation. *Earth Interactions* 4 (4):1-29.
- Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M., Francis, R. C. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull. Amer. Meteorol. Soc.* 78:1069-1079.

- Manzanilla, S. R. 1989. The 1982-1983 El Niño event recorded in dentinal growth layers in teeth of Peruvian dusky dolphins (*Lagenorhynchus obscurus*). Can. J. Zool. 67:2120-2125.
- McFarlane, G. A., King, J. R., Beamish, R. J. 2000. Have there been recent changes in climate? Ask the fish. Prog. Oceanogr. 47:147-169.
- McGowan, J. A., Chelton, D. B., Conversi, A. 1996. Plankton patterns, climate, and change in the California Current. CalCOFI Rep. 37:45-68.
- McGowan, J. A., Cayan, D. R., Dorman, L. M. 1998. Climate-ocean variability and ecosystem response in the Northeast Pacific. Science 281:210-217.
- McPhaden, M. J., Zhang, D. 2002. Slowdown of the meridional overturning circulation in the upper Pacific Ocean. Nature 415:603-608.
- Mestas-Núñez, A. M., Enfield, D. B. 2001. Eastern equatorial Pacific SST variability: ENSO and non-ENSO components and their climatic associations. J. Clim. 14:391-402.
- Miller, A. J., Cayan, D. R., Barnett, T. P., Graham, N. E., Oberhuber, J. M. 1994. The 1976-77 climate shift of the Pacific Ocean. Oceanography 7(1):21-26.
- Miller, A. J., Schneider, N. 2000. Interdecadal climate regime dynamics in the North Pacific Ocean: theories, observations and ecosystem impacts. Prog. Oceanogr. 47:355-379.
- Minobe, S. 1997. A 50-70 year climatic oscillation over the North Pacific and North America. Geophys. Res. Lett. 24:683-686.
- Minobe, S. 1999. Resonance in bidecadal and pentadecadal climate oscillations over the North Pacific: role in climatic regime shifts. Geophys. Res. Lett. 26:855-858.
- Minobe, S. 2002. Interannual to interdecadal changes in the Bering Sea and concurrent 1998/99 changes over the North Pacific. Prog. Oceanogr. in press.
- Moron, V., Vautard, R., Ghil, M. 1998. Trends, interdecadal and interannual oscillations in global sea-surface temperatures. Clim. Dynam. 14:545-569.
- Muck, P. 1989. Major trends in the pelagic ecosystem off Peru and their implications for management. In: Pauly, D., Muck, P., Mendo, J., Tsukayama, I. (eds). The Peruvian upwelling system: dynamics and interactions, ICLARM Conf. Proc. 18, pp. 386-403.
- Musick, J. A. 1999. Life in the Slow Lane: Ecology and Conservation of Long-Lived Marine Animals. Am. Fish. Soc. Symp. 23, 265 pp.
- Mysak, L. A. 1986. El Niño, interannual variability and fisheries in the northeast Pacific Ocean. Can. J. Fish. Aquat. Sci. 43:464-497.

- Neelin, J. D., Battisti, D. S., Hirst, A. C., Jin, F-F., Wakata, Y., Yamagata, T., Zebiak, S. E. 1998. ENSO theory. *J. Geophys. Res. – Oceans* 103:14,261-14,290.
- Peterson, W. T., Mackas, D.L. 2001. Shifts in zooplankton abundance and species composition off central Oregon and southwestern British Columbia. *PICES Press* 9(2):28-31.
- Parker, D. E., Folland, C. K., Jackson, M. 1996. Marine surface temperature: observed variations and data requirements. *Climatic Change* 31:559-600.
- Philander, S. G. H. 1990. *El Niño, La Niña and the Southern Oscillation*. Academic Press, New York, 289 p.
- Philander, S. G. H. 1999. A review of tropical ocean-atmosphere interactions. *Tellus* 51:71-90.
- Pierce, D. W., Barnett, T. P., Latif, M. 2000. Connections between the Pacific Ocean tropics and midlatitudes on decadal timescales. *J. Clim.* 13:1173-1194.
- Polovina, J. J. 1996. Decadal variation in the trans-Pacific migration of northern bluefin tuna (*Thunnus thynnus*) coherent with climate-induced change in prey abundance. *Fish. Oceanogr.* 5(2):114-119.
- Polovina, J. J., Mitchum, G. T., Graham, N. E., Craig, M. P., DeMartini, E. E., Flint, E. N. 1994. Physical and biological consequences of a climate event in the central North Pacific. *Fish. Oceanogr.* 3(1):15-21.
- Polovina, J. J., Mitchum, G. T., Evans, G. T. 1995. Decadal and basin-scale variation in mixed layer depth and the impact on biological production in the Central and North Pacific, 1960-88. *Deep-Sea Res. Pt. I* 42:1701-1716.
- Quinn, W. H., Neal, V. T., Antunez de Mayolo, S. E. 1987. El Niño occurrences over the past four and a half centuries. *J. Geophys. Res. - Oceans* 92:14,449-14,461.
- Rajagopalan, B., Lall, U., Cane, M. A. 1997. Anomalous ENSO occurrences: an alternate view. *J. Clim.* 10:2351-2357.
- Ramirez, P. 1986. Distribucion y alimentacion de la ballena Bryde durante al fenomeno "El Niño" 1982-1983. *Bol. ERFEN* 17:20-27.
- Reynolds, R. W., Smith, T. M. 1994. Improved global sea surface temperature analyses. *J. Clim.* 7:929-94.
- Ribic, C. A., Ainley, D. G., Spear, L. B. 1992. Effects of El Niño and La Niña on seabird assemblages in the equatorial Pacific. *Mar. Ecol. Prog. Ser.* 80:109-124.

- Rodbell, D. T., Seltzer, G. O., Anderson, D. M., Abbott, M. B., Enfield, D. B., Newman, J. H. 1999. An ~15,000-year record of El Niño-driven alluviation in southwestern Ecuador. *Science* 283:516-520.
- Roemmich, D., McGowan, J. 1995. Climatic warming and the decline of zooplankton in the California Current. *Science* 267:1324-1326.
- Salstein, D. A., Rosen, R. D. 1984. El Niño and the Earth's rotation. *Oceanus* 27(2):52-57.
- Sandweiss, D. H., Maasch, K. A., Burger, R. L., Richardson, J. B. I., Rollins, H. B., Clement, A. 2001. Variation in Holocene El Niño frequencies: Climate records and cultural consequences in ancient Peru. *Geology* 29: 603-606.
- Schreiber, R. W., Schreiber, E. A. 1984. Central Pacific seabirds and the El Niño Southern Oscillation: 1982 to 1983 perspectives. *Science* 225:713-716.
- Schwartzlose, R. A., Alheit, J., Bakun, A., Baumgartner, T. R., Cloete, R., Crawford, R. J. M., Fletcher, W. J., Green-Ruiz, Y., Hagen, E., Kawasaki, T., Lluch-Belda, D., Lluch-Cota, S. E., MacCall, A. D., Matsuura, Y., Nevárez-Martínez, M. O., Parrish, R. H., Roy, C., Serra, R., Shust, K. V., Ward, M. N., Zuzunaga, J. Z. 1999. Worldwide large-scale fluctuations of sardine and anchovy populations. *S. Afr. J. Mar. Sci.* 21:289-347.
- Schwing, F. B., Moore, C. 2000. A year without a summer for California, or a harbinger of a climate shift? *EOS, Trans. AGU* 81(27):301 ff.
- Schwing, F. B., Murphree, T., Green, P. M. 2002. The Northern Oscillation Index (NOI): a new climate index for the northeast Pacific. *Prog. Oceanogr.* 53:115-139.
- Setoh, T., Imawaki, S., Ostrovskii, A., Umatani, S-I. 1999. Interdecadal variations of ENSO signals and annual cycles revealed by wavelet analysis. *J. Oceanogr.* 55:385-394.
- Shane, S. H. 1995. Relationship between pilot whales and Risso's dolphins at Santa Catalina Island, California, USA. *Mar. Ecol. Prog. Ser.* 123:5-11.
- Sharp, G. D. 1992. Fishery catch records, El Niño/Southern Oscillation, and longer-term climate change as inferred from fish remains in marine sediments. In: Diaz HF, Markgraf V (eds) *El Niño: historical and paleoclimatic aspects of the Southern Oscillation*, Cambridge University Press, Cambridge, pp. 379-417.
- Sharp, G. D., McLain, D. R. 1993. Fisheries, El Niño-Southern Oscillation and upper-ocean temperature records: an eastern Pacific example. *Oceanography* 6(1):13-22.
- Southward, A. J., Boalch, G. T., Mattock, L. 1988. Fluctuations in the herring and pilchard fisheries of Devon and Cornwall linked to change in climate since the 16th century. *J. Mar. Biol. Assoc. UK* 68:423-445.

- Stephens, C., Levitus, S., Antonov, J., Boyer, T. P. 2001. On the Pacific Ocean regime shift. *Geophys. Res. Lett.* 28:3721-3724.
- Strutton, P. G., Chavez, F. P. 2000. Primary productivity in the equatorial Pacific during the 1997-1998 El Niño. *J. Geophys. Res.* 105:26,089-26,101.
- Sydeman, W. J., Allen, S. J. 1999. Pinniped population dynamics in central California: correlations with sea surface temperature and upwelling indices. *Mar. Mammal Sci.* 15:446-461.
- Sydeman, W. J., Hester, M. M., Thayer, J. A., Gress, F., Martin, P., Buffa, J. 2001. Climate change, reproductive performance and diet composition of marine birds in the southern California Current system, 1969-1997. *Prog. Oceanogr.* 49:309-329.
- Tomita, T., Wang, B., Yasunari, T., Nakamura, H. 2001. Global patterns of decadal-scale variability observed in sea surface temperature and lower-tropospheric circulation fields. *J. Geophys. Res. - Oceans* 106:26,805-26,816.
- Tovar, H., Guillén, V., Cabrera, D. 1987. Reproduction and population levels of Peruvian guano birds, 1980 to 1986. *J. Geophys. Res. - Oceans* 92:14,445-14,448.
- Trenberth, K. E., Hoar, T. J. 1996. The 1990-1995 El Niño-Southern Oscillation event: longest on record. *Geophys. Res. Lett.* 23:57-60.
- Trenberth, K. E., Hurrell, J. W. 1994. Decadal atmosphere-ocean variations in the Pacific. *Clim. Dyn.* 9:303-319.
- Trenberth, K. E., Stepaniak, D. P. 2001. Indices of El Niño evolution. *J. Clim.* 14:1697-1701.
- Trillmich, F., Limberger, D. 1985. Drastic effects of El Niño on Galapagos pinnipeds. *Oecologia* 67:19-22.
- Tynan, C. T. 1999. Redistributions of cetaceans in the southeast Bering Sea relative to anomalous oceanographic conditions during the 1997 El Niño. *PICES Sci. Rep.* 10:115-117.
- Valle, C. A., Cruz, F., Cruz, J. B., Merlen, G., Coulter, M. C. 1987. The impact of the 1982-1983 El Niño-Southern Oscillation on seabirds in the Galapagos Islands, Ecuador. *J. Geophys. Res. - Oceans* 92:14,437-14,444.
- Veit, R. R., Pyle, P., McGowan, J. A. 1996. Ocean warming and long-term change in pelagic bird abundance within the California current system. *Mar. Ecol. Prog. Ser.* 139:11-18.

- Venrick, E. L., McGowan, J. A., Cayan, D. R., Hayward, T. L. 1987. Climate and chlorophyll a: long-term trends in the central North Pacific Ocean. *Science* 238:70-72.
- Wallace, J. M., Rasmusson, E. M., Mitchell, T. P., Kousky, V. E., Sarachik, E. S., von Storch, H. 1998. On the structure and evolution of ENSO-related climate variability in the tropical Pacific: Lessons from TOGA. *J. Geophys. Res. - Oceans* 103:14,241-14,260.
- Ware, D. M. 1995. A century and a half of change in the climate of the NE Pacific. *Fish. Oceanogr.* 4 (4):267-277.
- Ware, D. M., Thomson, R. E. 1991. Link between long-term variability in upwelling and fish production in the northeast Pacific Ocean. *Can. J. Fish. Aquat. Sci.* 48:2296-2306.
- Ware, D. M., Thomson, R. E. 2000. Interannual to multidecadal timescale climate variations in the northeast Pacific. *J. Clim.* 13:3209-3220.
- Watanabe, M., Nitta, T. 1999. Decadal changes in the atmospheric circulation and associated surface climate variations in the northern hemisphere winter. *J. Clim.* 12:494-510.
- Weickmann, K. M., Robinson, W. A., Penland, M. C. 2000. Stochastic and oscillatory forcing of global atmospheric angular momentum. *J. Geophys. Res. – Atmos.* 105:15543-15557.
- Wikelski, M., Thom, C. 2000. Marine iguanas shrink to survive El Niño. *Nature* 403:37.
- Yáñez, E., Barbieri, M. A., Santillán, L. 1992. Long-term environmental variability and pelagic fisheries in Talcahuano, Chile. *S. Afr. J. Mar. Sci.* 12:175-188.
- Yasuda, I., Sugisaki, H., Watanabe, Y., Minobe, S., Oozeki, Y. 1999. Interdecadal variations in Japanese sardine and ocean/climate. *Fish. Oceanogr.* 8(1):18-24.
- Zhang, Y., Wallace, J. M., Battisti, D. S. 1997. ENSO-like interdecadal variability. *J. Clim.* 10:1004-1020.
- Zhang, R-H., Rothstein, L. M., Busalacchi, A. J. 1998a. Origin of upper-ocean warming and El Niño change on decadal scales in the tropical Pacific Ocean. *Nature* 391:879-883.
- Zhang, X., Sheng, J., Shabbar, A. 1998b. Modes of interannual and interdecadal variability of Pacific SST. *J. Clim.* 11:2556-2569.

Table 1. Linear trends in monthly anomalies, 1980-2001, of sea surface temperature and thermocline depth in ETP and North Pacific regions (Fig. 4). Data from NCEP (NOAA/NWS/National Center for Environmental Prediction) monthly hindcast fields (Behringer et al. 1998). P levels: * $p < .05$, *** $p < .001$

	SST ($^{\circ}\text{C y}^{-1}$)	Thermocline Depth (m y^{-1})
NINO3	-0.013 NS	-0.36 * ²
ETP Core Area	+0.003 NS	-0.28 *** ³
California Current	+0.009 NS	+0.15 NS
Central North Pacific	+0.047 *** ¹	+0.13 NS

¹ +0.009 NS for 1980-1997

² -0.041 NS for 1980-1998, +0.647 * for 1984-1998

³ -0.088 NS for 1980-1998, +0.486 *** for 1984-1998

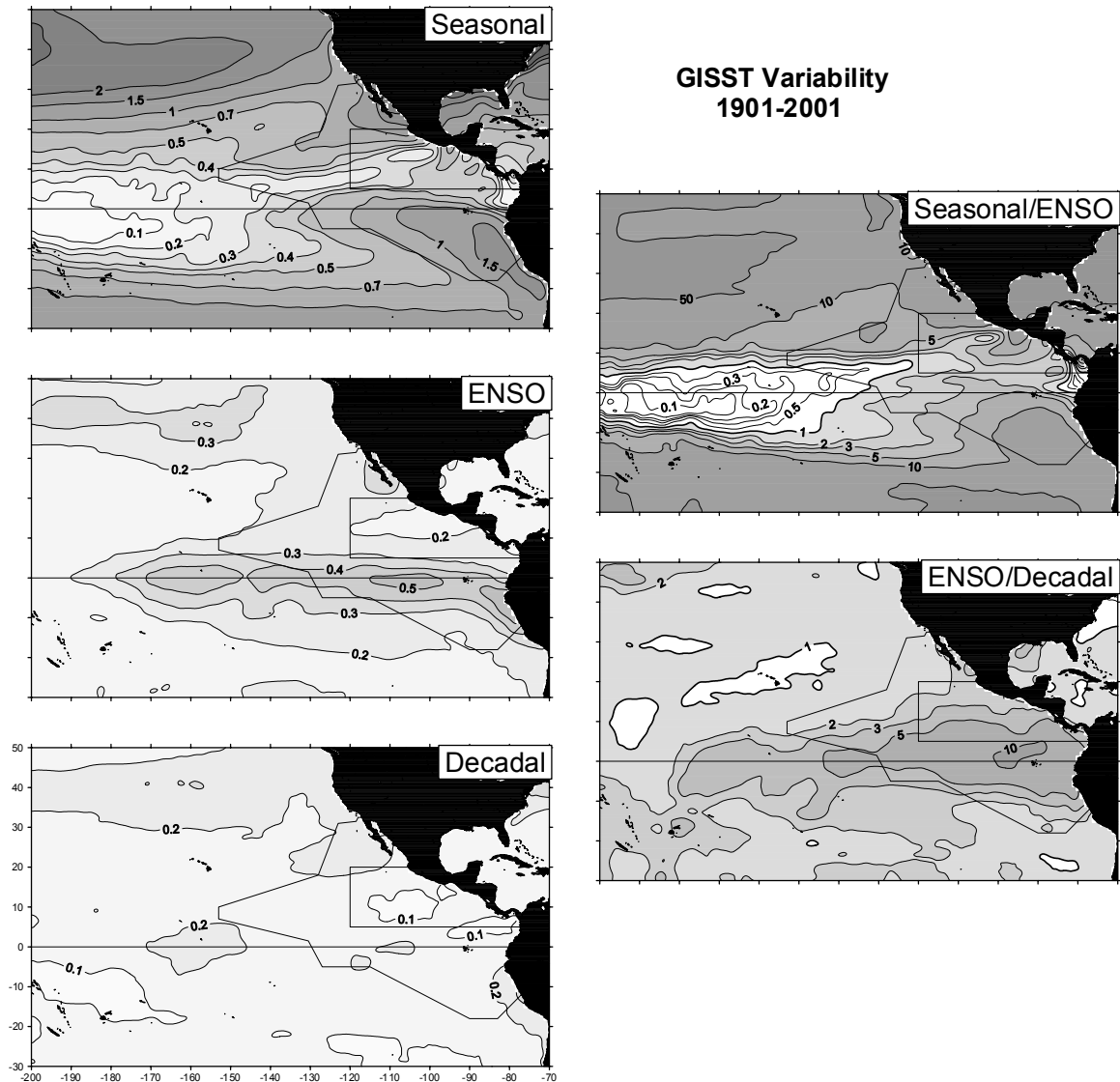


Figure 1. (Left) variances of sea surface temperature during 1901-2001 (expressed as standard deviation, °C), summed in three spectral bands: Seasonal (0.98-1.02 years), ENSO (1.8-7.2 years), and Decadal (9.2-50.5 years). (Right) ratios of Seasonal/ENSO and ENSO/Decadal variances. Data from UK Meteorological Office Global Sea-ice SST (GISST, v. 2.3b) data (Parker et al. 1995), obtained from British Atmospheric Data Centre. Thin lines mark boundaries of ETP survey areas.

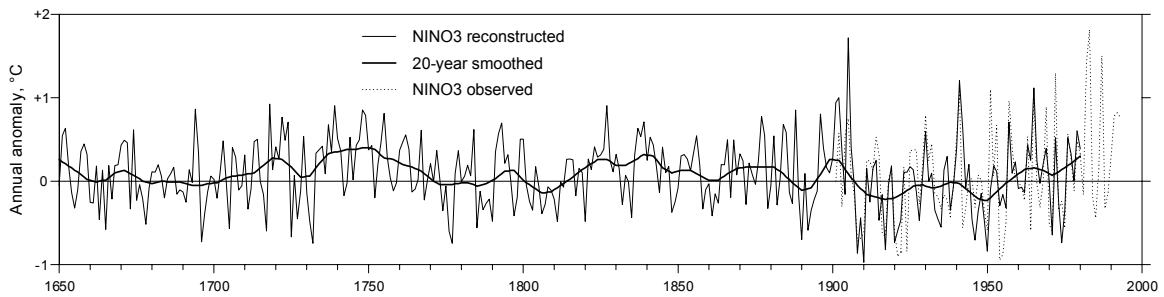


Figure 2. Annual sea surface temperature variability in the eastern equatorial Pacific since 1650 (Mann et al. 2000). “20-year smoothed” is the NINO3 reconstructed series smoothed by local regression (LOESS) within a 20-year span.

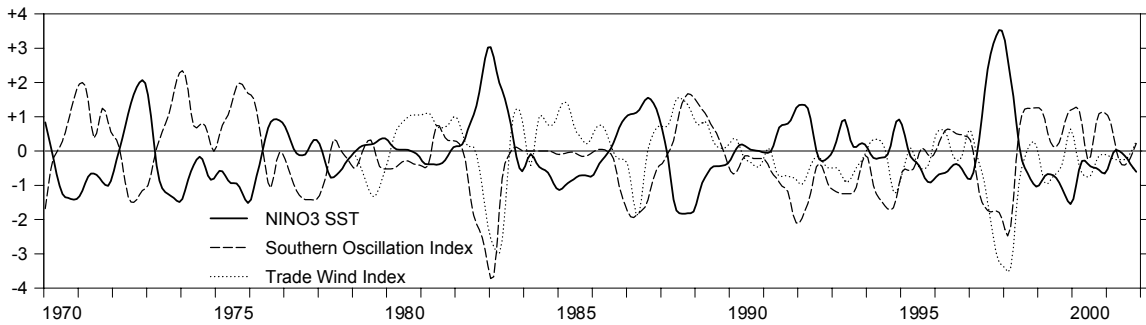


Figure 3. ENSO indices 1970-2001: NINO3 SST anomaly (5°S - 5°N 150 - 90°W , $^{\circ}\text{C}$), Southern Oscillation Index (Tahiti – Darwin SLP, standardized), Trade Wind Index (850mb easterly wind velocity 5°S - 5°N , 135 - 120°W , standardized). Monthly values from NOAA/NCEP/Climate Prediction Center (<http://www.cpc.ncep.noaa.gov/data/indices/>), smoothed using method of running medians known as 4(3RSR)2H (S-Plus 2000, MathSoft, Inc.).

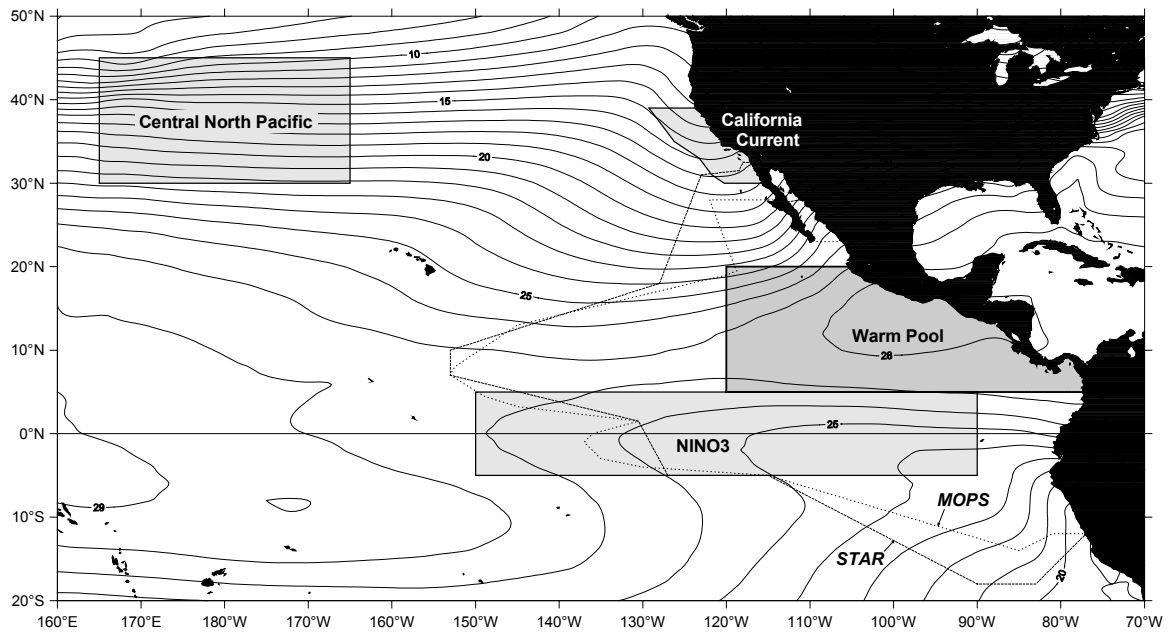


Figure 4. Surface temperature and thermocline depth time series areas, with MOPS and STAR survey areas. SST contours from the Reynolds and Smith (1994) climatology.

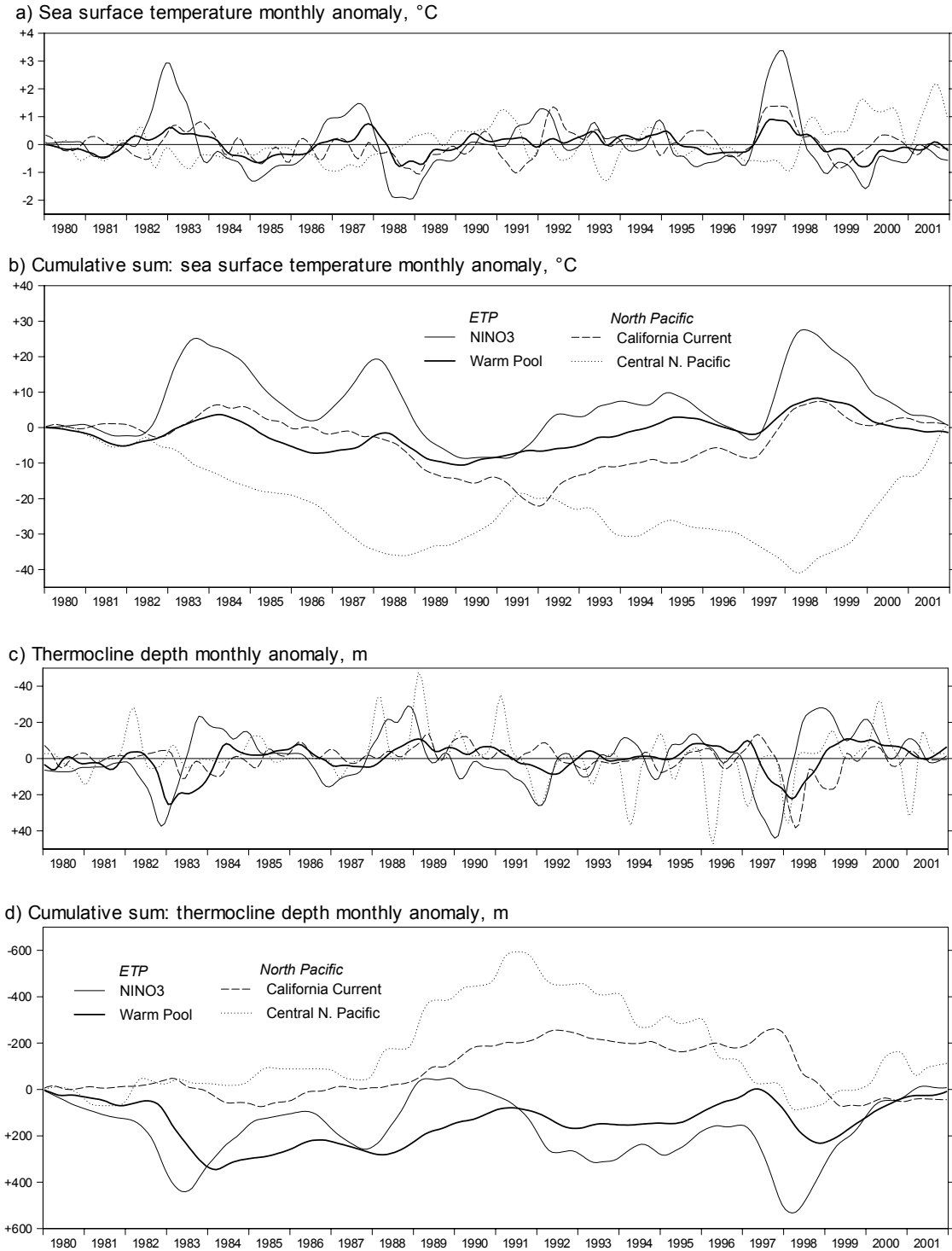


Figure 5. Time series of 1980-2001 sea surface temperature and thermocline depth monthly anomalies and cumulative sums in ETP and North Pacific regions (see Fig. 5). Thermocline depth calculated as 20 °C isotherm depth in ETP and depth of maximum temperature gradient in North Pacific. Data from NCEP (NOAA/NWS/National Center for Environmental Prediction) monthly hindcast fields (Behringer et al. 1998).

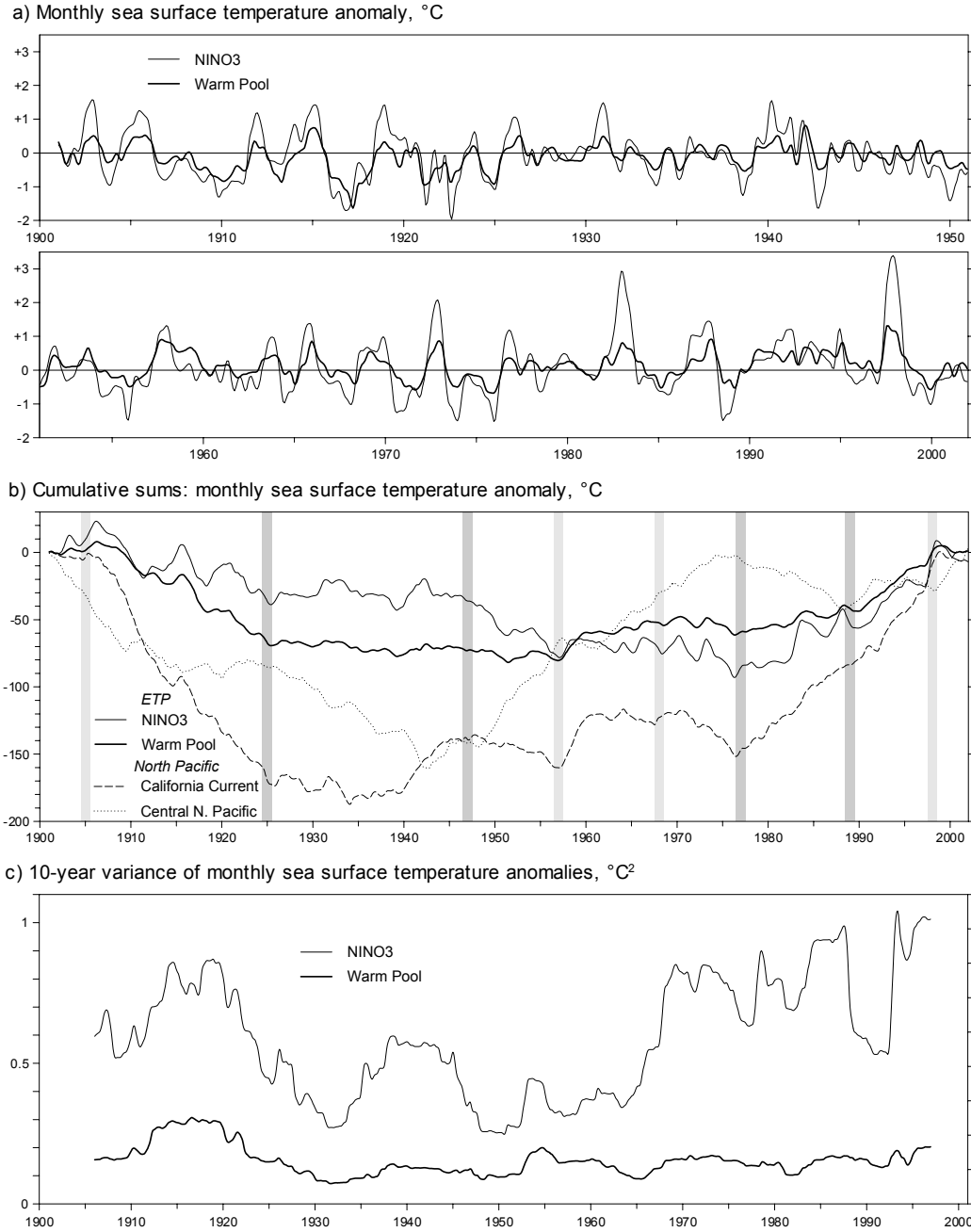


Figure 6. Sea surface temperature monthly anomaly time series (a, only ETP series shown for clarity), cumulative sums (b), and 10-year running variance (c, ETP series only), for 1901-2001 in ETP and North Pacific regions (see Fig. 5). Shaded bars mark climate shifts from published analyses of ocean and air temperature and atmospheric pressure data (light shading = limited evidence): 1906-07², 1924-25^{2-5,8}, 1946-47^{2-5,8,9}, 1956-57², 1967-68², 1976-77¹⁻⁹, 1988-89^{1,5-8}, 1998-1999 (see text). References: 1) Trenberth and Hurrell (1994), 2) Ware (1995), 3) Mantua et al. (1997), 4) Minobe (1997), 5) Beamish et al. (1999), 6) Watanabe and Nitta (1999), 7) Hare and Mantua (2000), 8) McFarlane et al. (2000), 9) Biondi et al. (2001). Area means from UK Meteorological Office Global Sea-ice SST (GISST, v. 2.3b) data (Parker et al. 1995), obtained from British Atmospheric Data Centre.

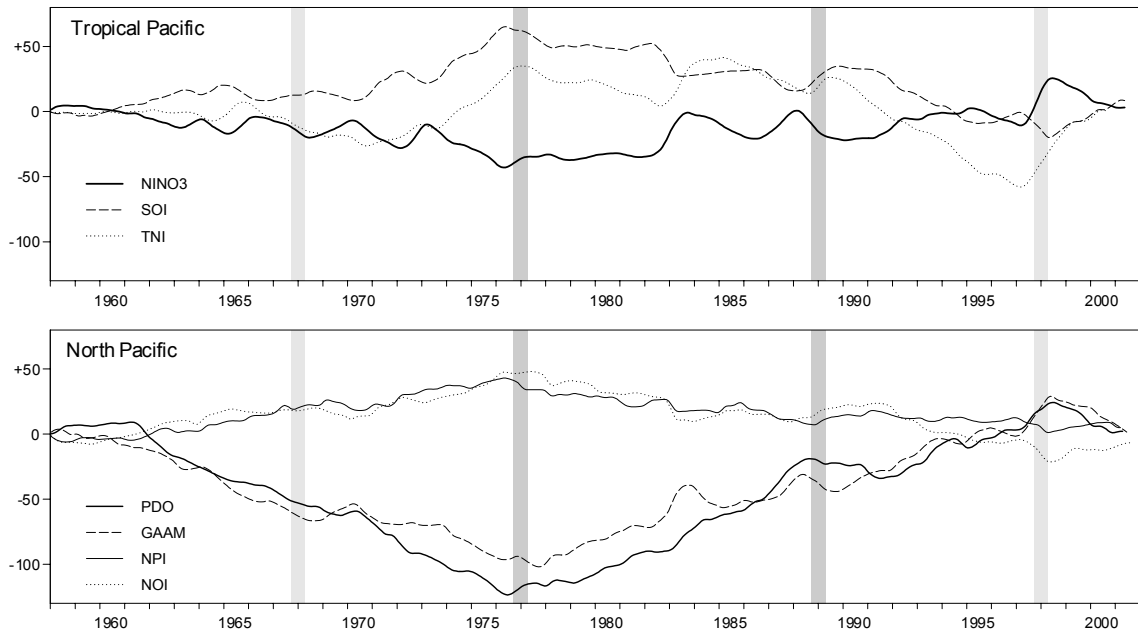


Figure 7. Cumulative sums of monthly normalized time series of climate indices from the tropical Pacific (top) and the North Pacific (bottom), 1958-2000. NINO3 = NINO3 SST anomaly (eastern equatorial Pacific), SOI = Southern Oscillation Index (surface pressure difference between Tahiti and Darwin), TNI = Trans-Niño Index (gradient of SST across eastern and central equatorial Pacific, Trenberth and Stepaniak 2001), PDO = Pacific Decadal Oscillation (leading principal component of North Pacific monthly SST variability; Mantua et al., 1997), GAAM = Global Atmospheric Angular Momentum (Weickmann et al. 2000), NPI = North Pacific Index (SLP 30N-65N, 160E-140W, Trenberth and Hurrell 1994), NOI = Extratropical Northern Oscillation Index (surface pressure difference between North Pacific High and Darwin, Schwing et al. 2002). Shaded bars mark published climate shifts from Fig. 6.

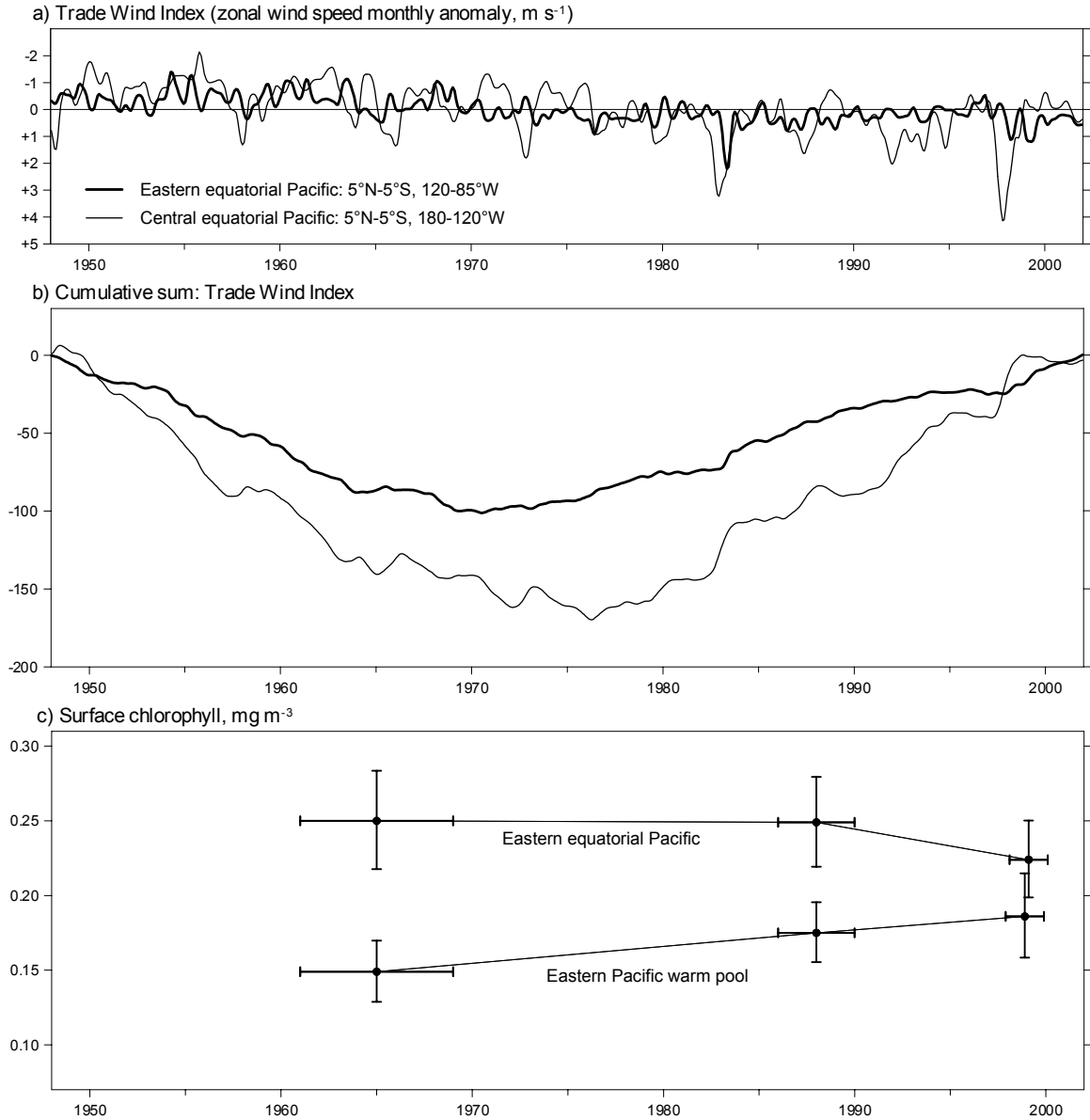


Figure 8. (A) Equatorial Pacific trade wind indices and (B) cumulative sums, 1948-2001. Monthly areal means calculated from NCEP Reanalysis data from NOAA-CIRES Climate Diagnostics Center web site at <http://www.cdc.noaa.gov/>. (C) Mean surface chlorophyll concentrations east of 120°W during August-November from gridded values of log-transformed observations for 1960-1969 (NODC World Ocean Database 2001, Conkright et al. 2002) and for 1986-1990 and 1998-2000 (Fiedler and Philbrick 2002). Vertical error bars represent 95% confidence limits estimated from the standard deviation of gridded values, assuming that autocorrelation and smoothing reduces the effective degrees of freedom by a factor of 10.

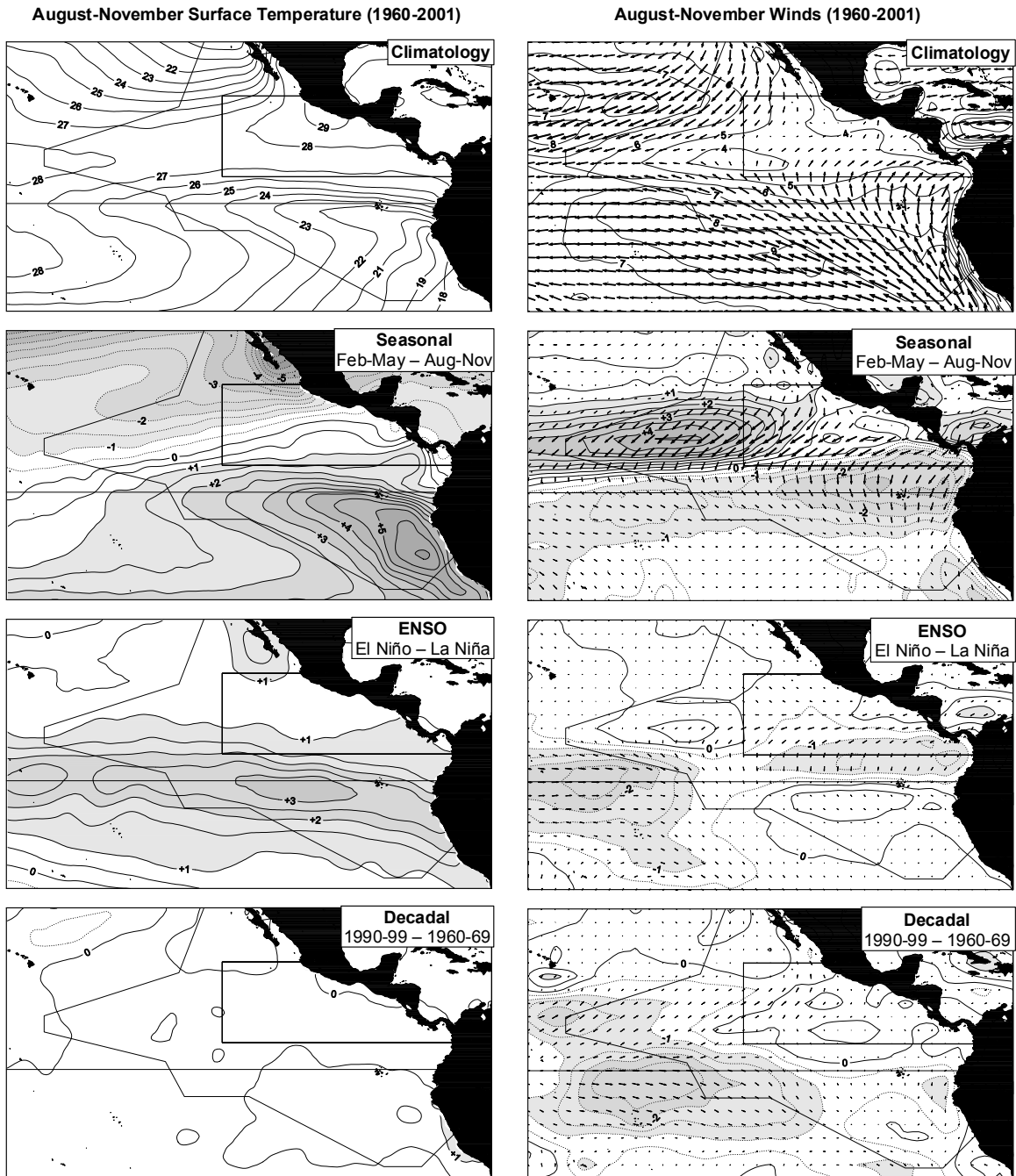


Figure 9. Environmental means and variability on three temporal scales in the ETP: August-November 1960-2001 climatologies, seasonal differences (February-May minus August-November), ENSO differences (El Niño years minus La Niña years), and decadal differences (1990's minus 1960's) for surface temperature (left, GISST, Parker et al. 1995) and wind speed and direction (right, NCEP Reanalysis data from NOAA-CIRES Climate Diagnostics Center web site at <http://www.cdc.noaa.gov/>). Thin lines mark boundaries of ETP survey areas.

APPENDIX A

Responses to CIE Reviewers

The CIE reviewers provided useful comments on this document. General suggestions for future field work will be carefully considered. All suggestions specific to this report were incorporated in the final report, with exceptions detailed below.

Ken Drinkwater

This paper was not combined with Fiedler and Philbrick (2002) because the two “Environmental Change in the Eastern Tropical Pacific” papers are being submitted for publication to two different journals. The review paper is of much broader interest.

Paul Thompson

The Hoppe et al. (2002) paper on apparent change in the tropical Atlantic is too speculative to make useful inferences about the ETP.

Hazel Oxenford

The organization of sections was not changed, to retain separation of the review of physical and biological variability from the original analyses.

George Hunt

Data and discussion of 1970’s change in frequency and amplitude of ENSO were added, but nothing is known about how this might affect dolphin stocks.